High energy pA collisions in CGC

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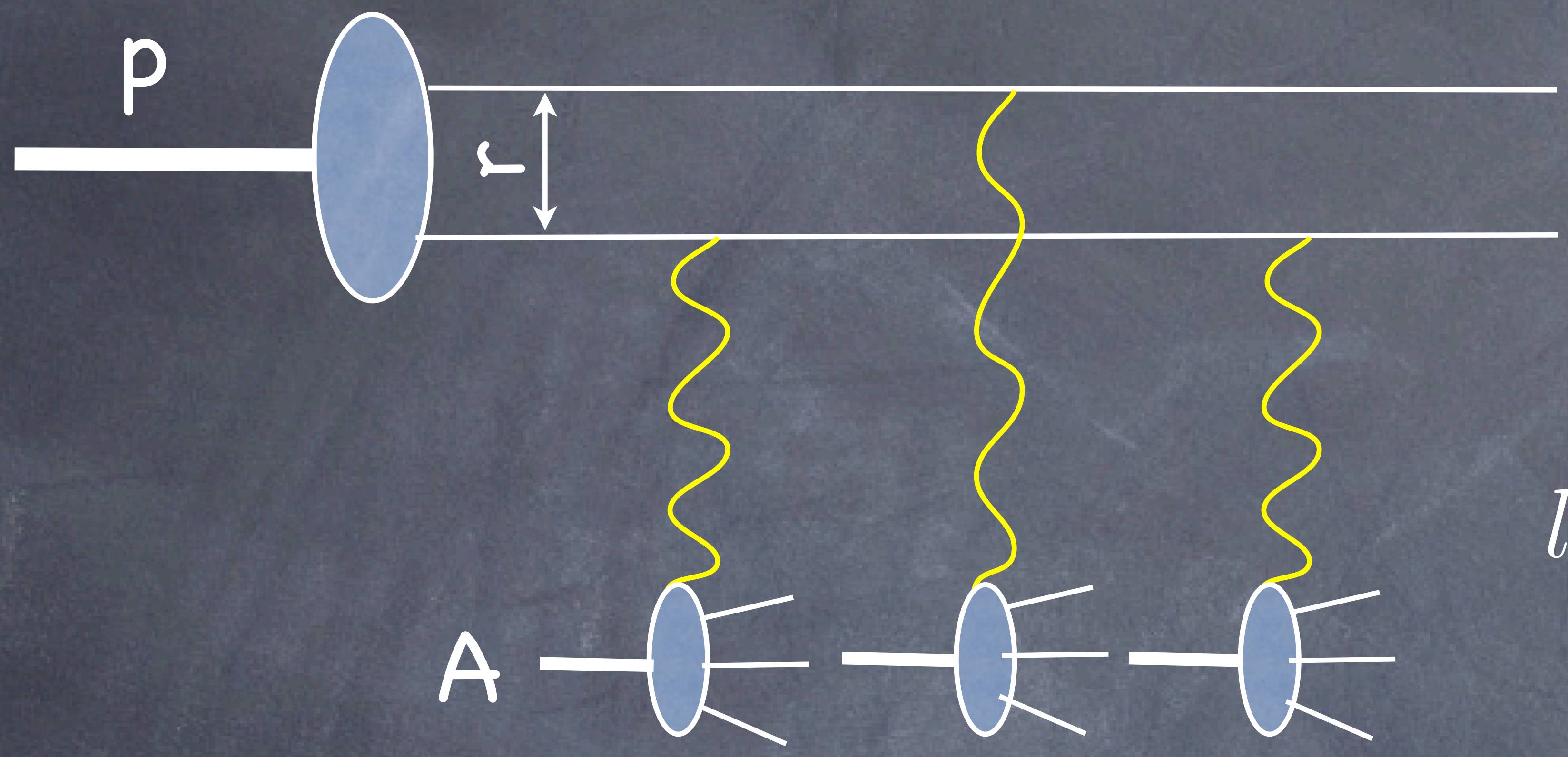
Nuclei as heavy as bulls through collision generate new states of matter

Hard Probes 2006, CA

Quasiclassical picture of pA collisions



- Kinematic regime: x<<1, α<<1
- Coherence length of qq pair

$$l_c \approx \frac{1}{k_-^q + k_-^{\bar{q}} - k_-^h} = \frac{1}{M_N x} \gg R_A$$

with $x = \frac{m_\perp}{\sqrt{s}} e^{-y}$

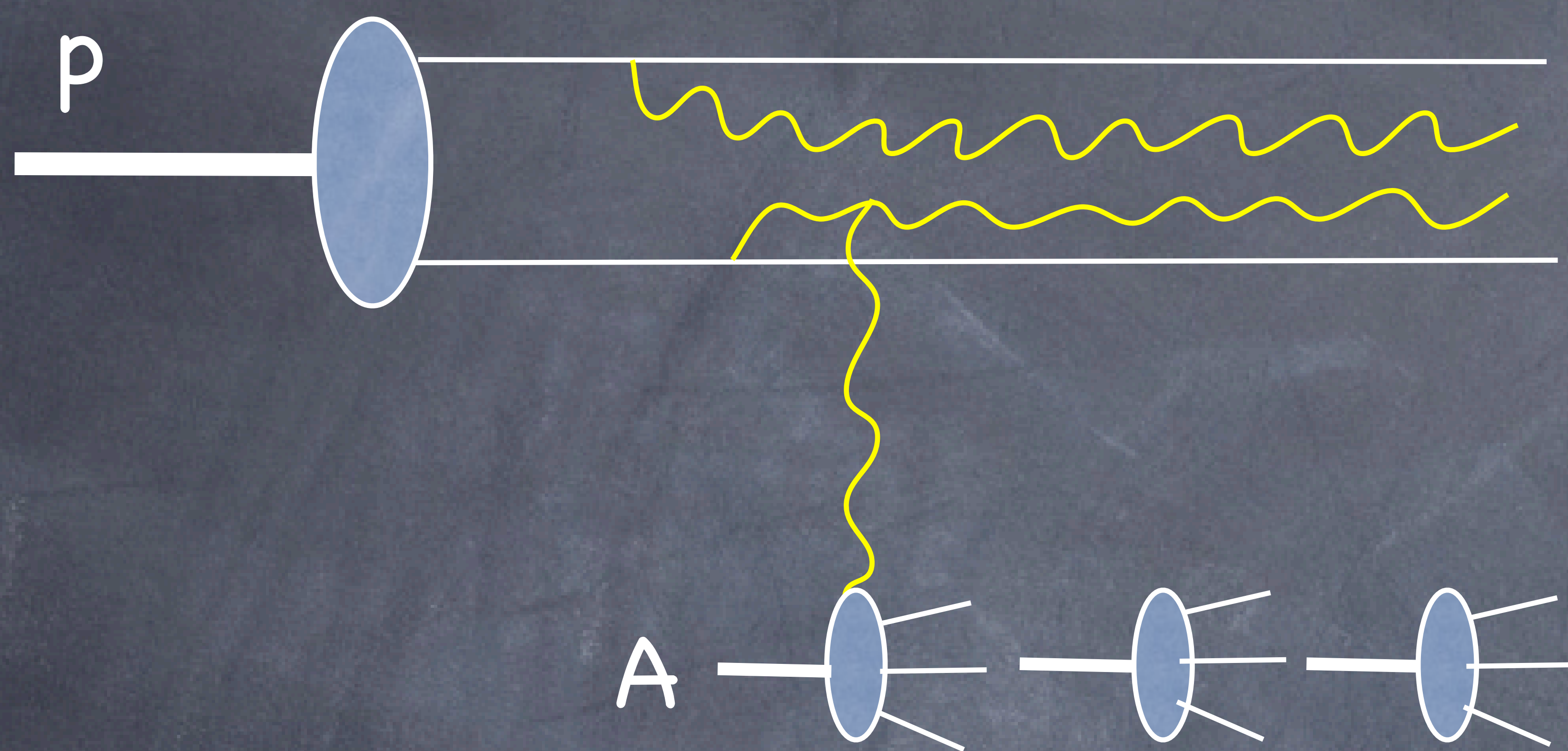
The dipole-nucleus cross section $\sigma_{q\bar{q}} = 2 \int d^2\underline{b}\, \mathrm{Im} N(x, \underline{r}, \underline{b})$

Quasiclassical-approximation: $\alpha_s \ln(1/x) \ll 1 \quad \alpha_s^2 A^{1/3} \sim 1$

$$\mathrm{Im} N(x, \underline{r}, \underline{b}) = 1 - \exp\left(-\underline{r}^2 Q_s^2/4\right)$$

A. Mueller,
McLerran-Venugopalan

Linear evolution

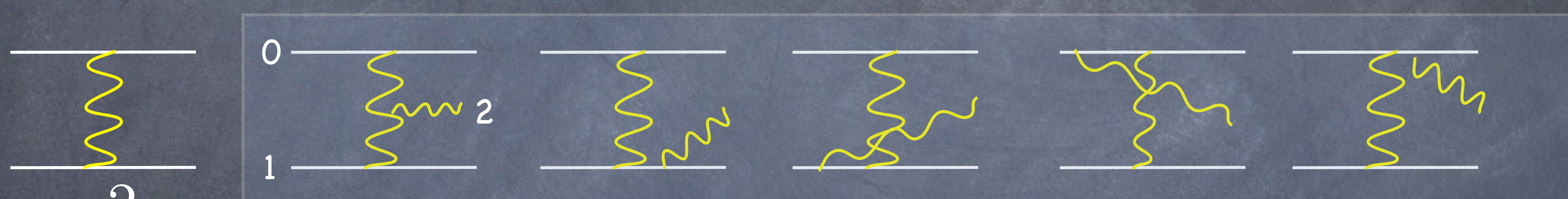


- Linear evolution regime

$$\alpha_s \ln(1/x) \sim 1 \qquad \alpha_s^2 A^{1/3} \ll 1$$

(BFKL)

COM:

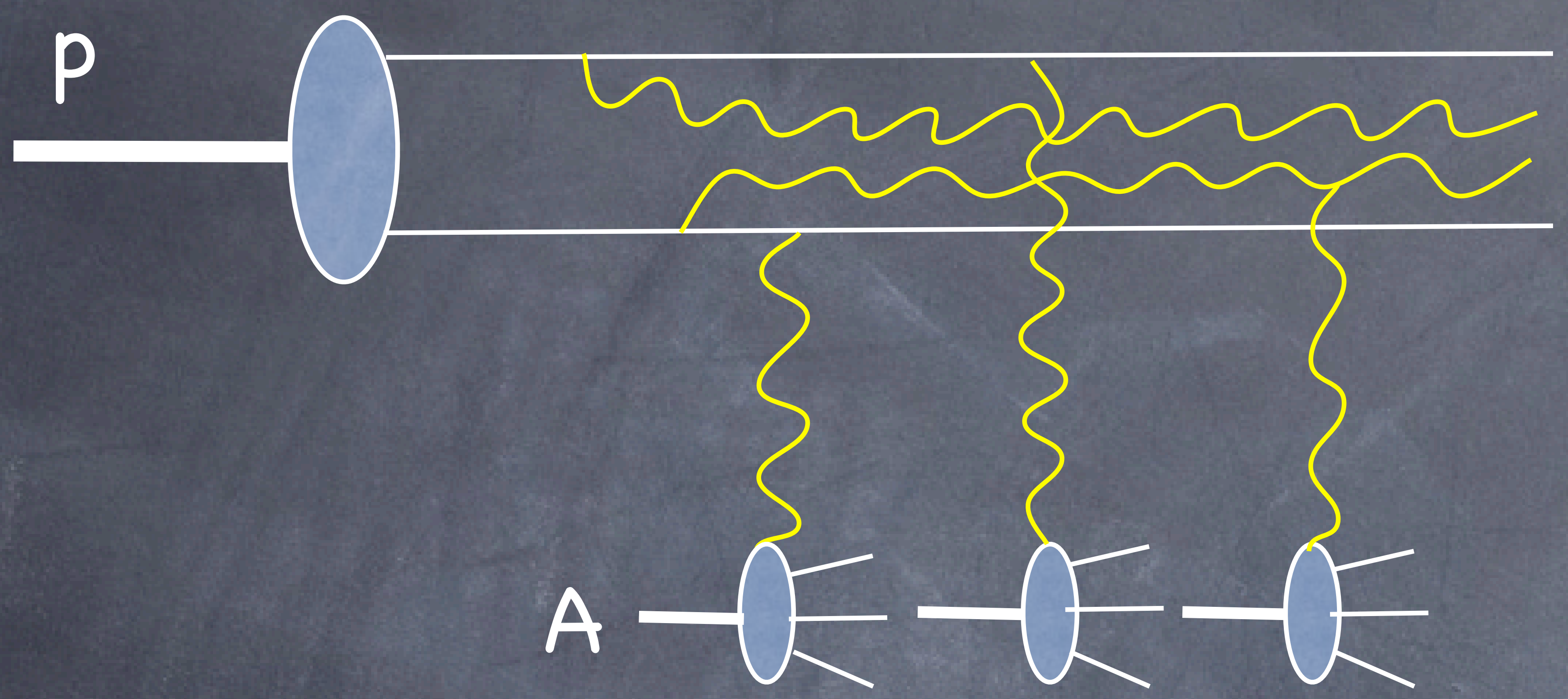


α_s^2

$\alpha_s^3 \ln(1/x)$

$$\partial_y N(\underline{x}_{01}) = \frac{\alpha_s}{2\pi} \int d^2x_2 \frac{\underline{x}_{01}^2}{\underline{x}_{12}^2\, \underline{x}_{20}^2} \left(N(\underline{x}_{12}) + N(\underline{x}_{20}) - N(\underline{x}_{01})\right)$$

High parton density



- Non-linear evolution regime

$$\alpha_s \ln(1/x) \sim 1\,, \quad \alpha_s^2 A^{1/3} \sim 1$$

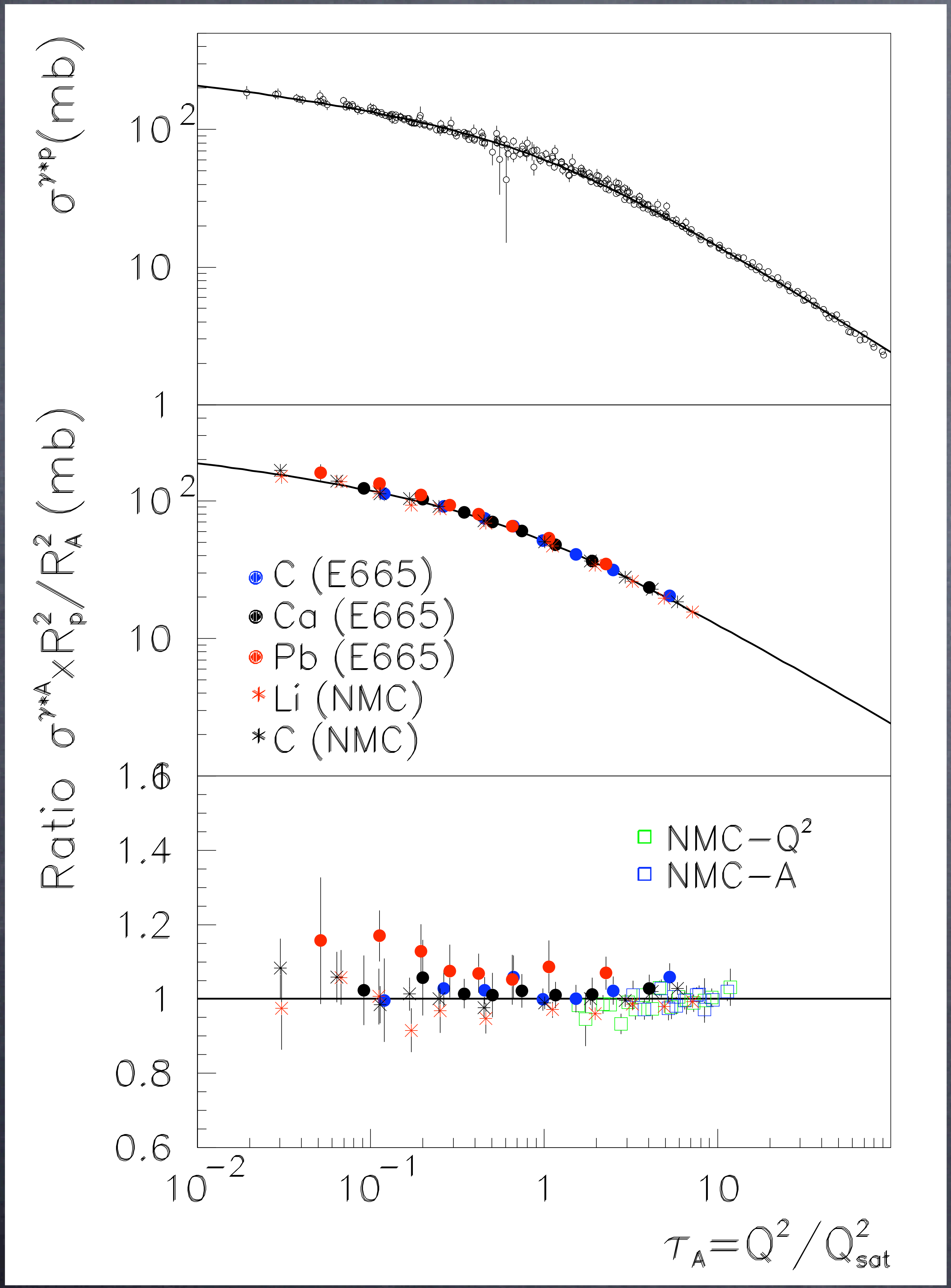
$$\partial_y N(\underline{x}_{01}) = \frac{\alpha_s}{2\pi}\int d^2x_2 \frac{\underline{x}_{01}^2}{\underline{x}_{12}^2\,\underline{x}_{20}^2}\left(N(\underline{x}_{12}) + N(\underline{x}_{20}) - N(\underline{x}_{01}) - N(\underline{x}_{12})N(\underline{x}_{20})\right)$$

Balitski, Kovchegov

The saturation scale $Q_s^2 = \Lambda^2\, A^{1/3} e^{\lambda y} e^{\lambda s/2}$

- Effective theory of high parton density QCD is “Color Glass Condensate”. JIMWLK

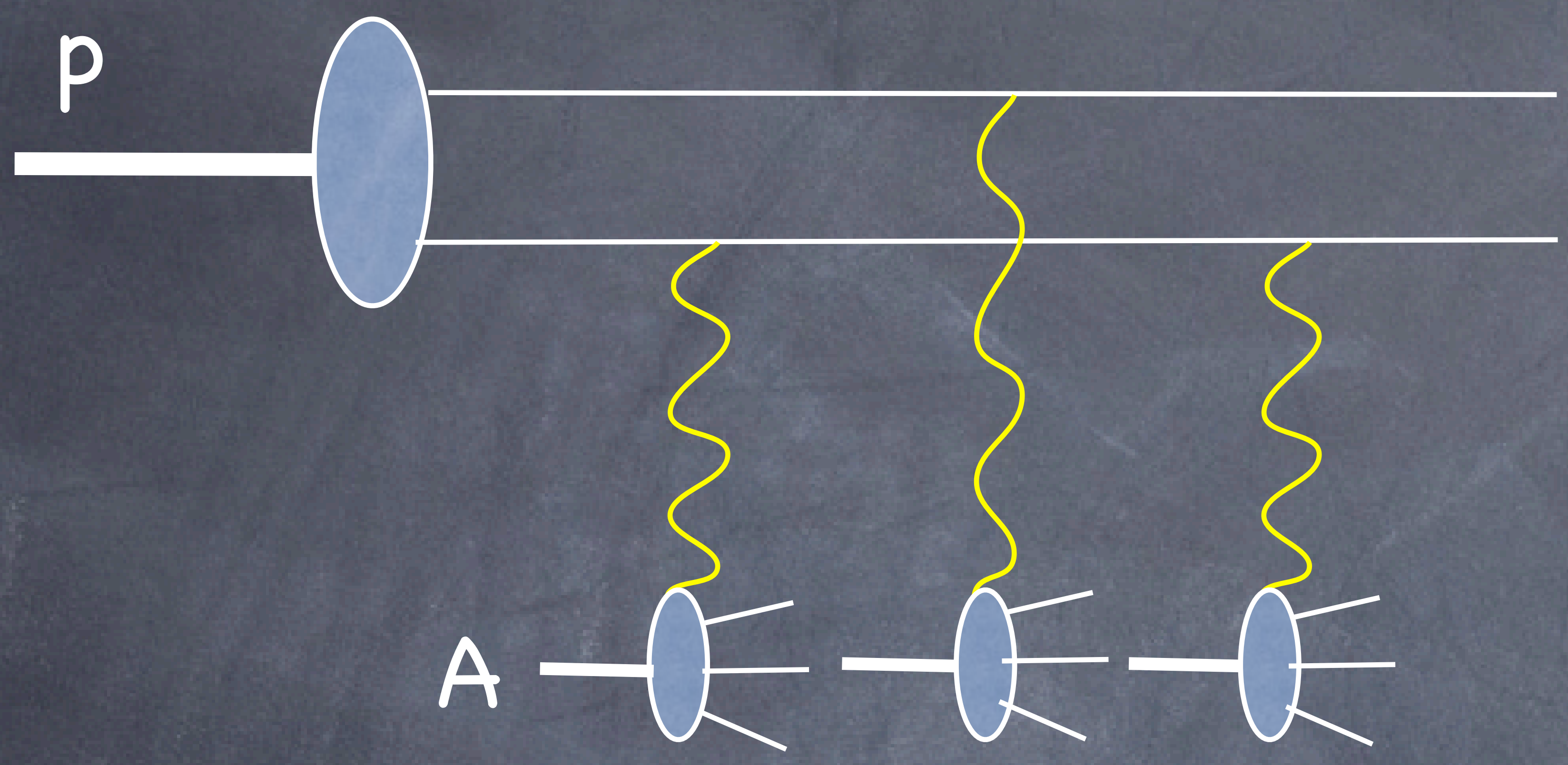
Geometric scaling in nuclei



- Scaling of DIS cross section with Q/Q_s is the direct signal of high parton density.

Stasto, Golec-Biernat, Kwiecinski
Armesto, Salgado, Wiedemann

Gluon Production



Kovchegov, A. Mueller; Kovchegov, KT

- Gluon interaction with the nucleus is instantaneous:

$$l_c = \frac{k_+}{k_\perp^2} \gg R_A$$

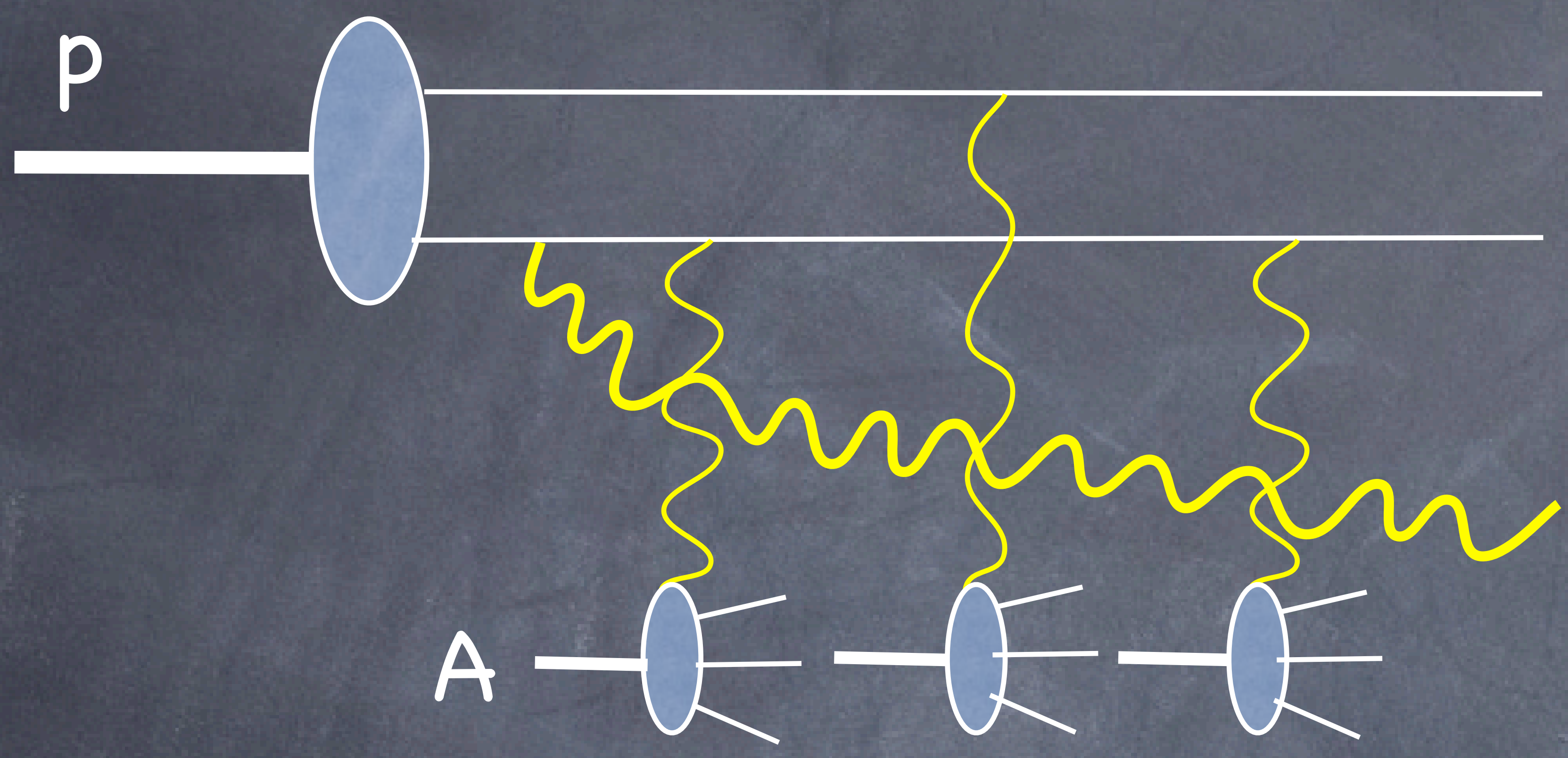
$$\frac{d\sigma^{pA}}{d^2k\,dy} = \frac{2\,\alpha_s}{C_F \underline{k}^2} \int d^2q\, \phi_p(\underline{q}, Y-y)\, \phi_A(\underline{k}-\underline{q}, y)$$

where $\phi(x, \underline{k}^2) = \dfrac{C_F}{\alpha_s (2\pi)^3} \displaystyle\int d^2b\, d^2z\, e^{-i\underline{k}\cdot\underline{z}} \nabla_z^2 N_G(\underline{z}, \underline{b}, y)$

is unintegrated gluon distribution function

see also Dumitru, McLerran

Gluon Production



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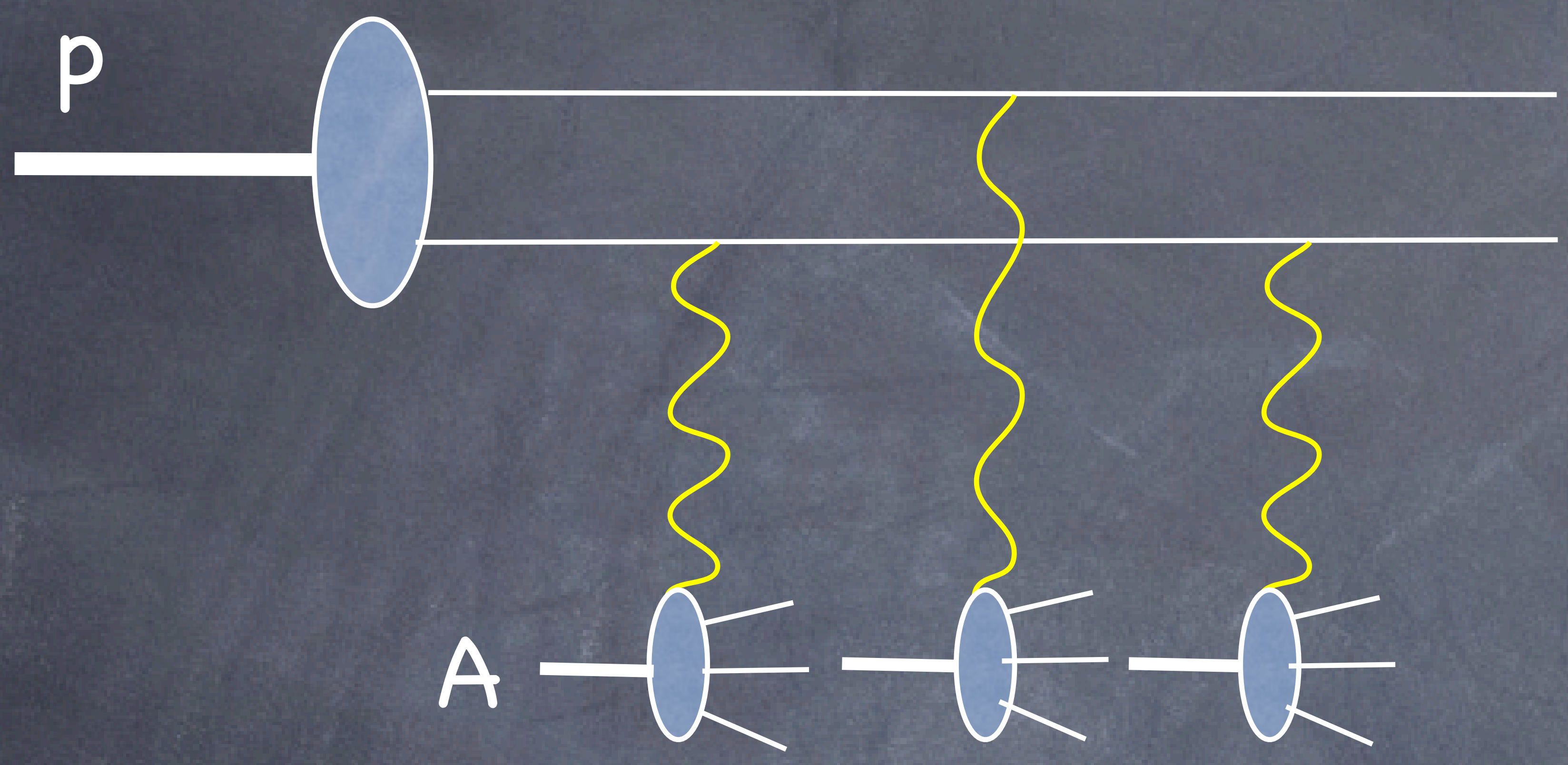

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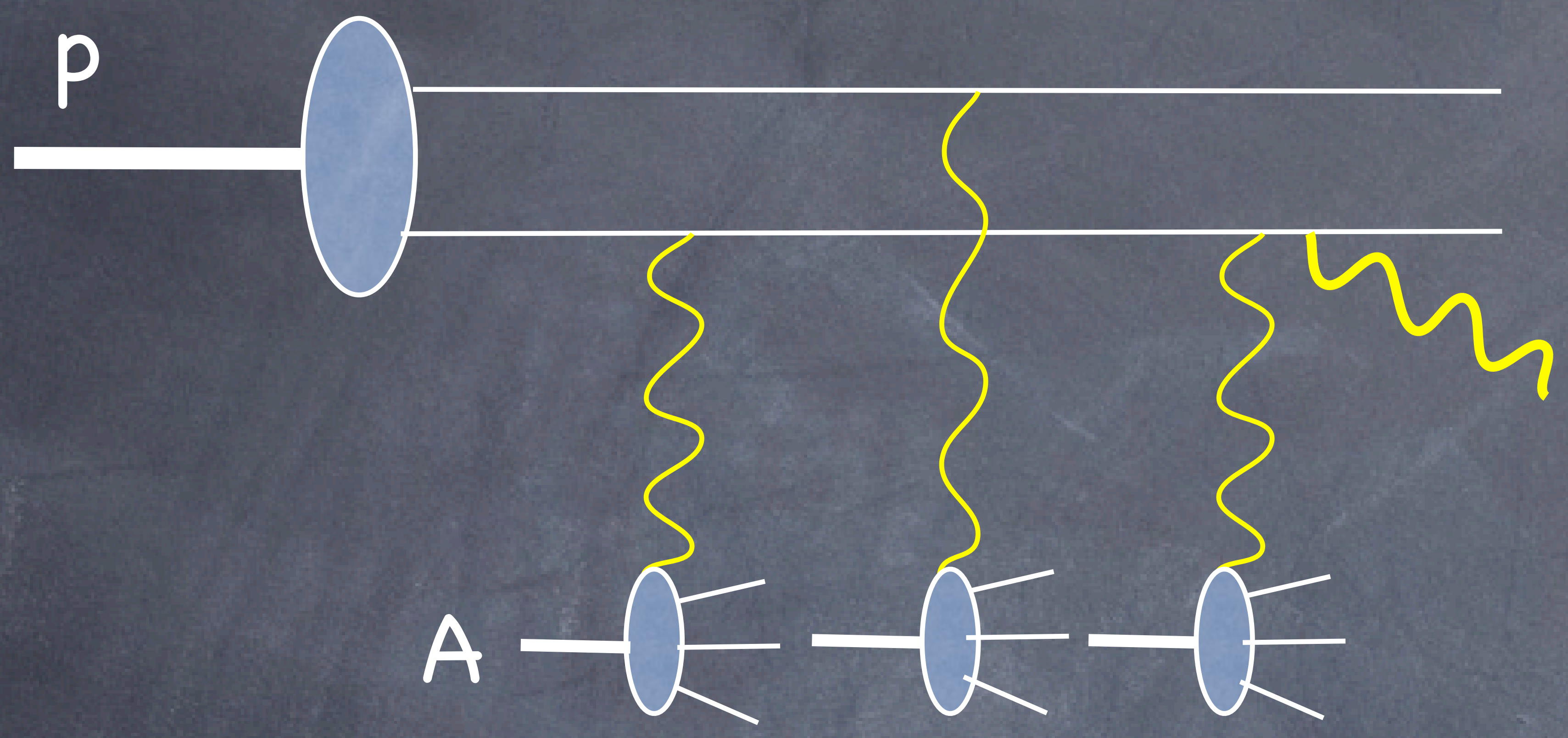

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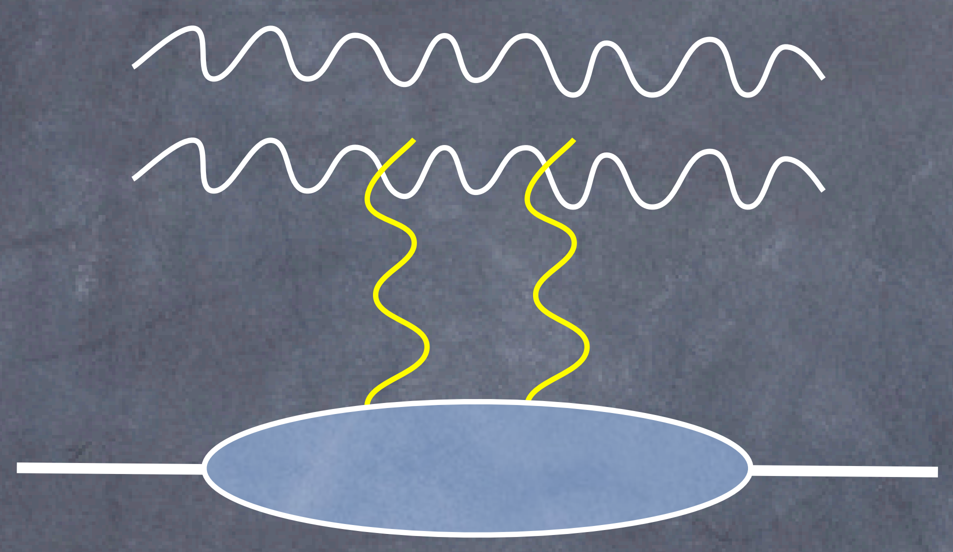
is unintegrated gluon distribution function

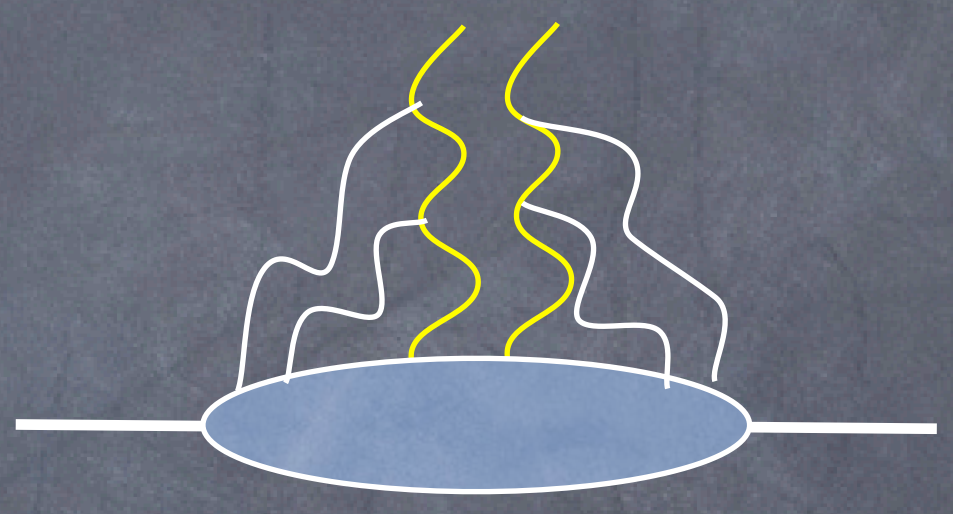
see also Dumitru, McLerran

k_T-factorization (Levin, Ryskin)

- In spite of explicit factorization breaking by each individual diagram, their sum can be factorized. (Kovchegov, KT) AGK rules?



Factorized gluon distribution



Weizsäcker-Williams gluon distribution

- No gauge is known in which the factorization would be explicit.

CGC vs shadowing models

- it's all about parameters

$$x \qquad \alpha_s^2 A^{1/3} \qquad \alpha_s \ln(1/x)$$

How small is x? Is $l_c >> R_A$?

Is A large enough to make higher twist effects important?

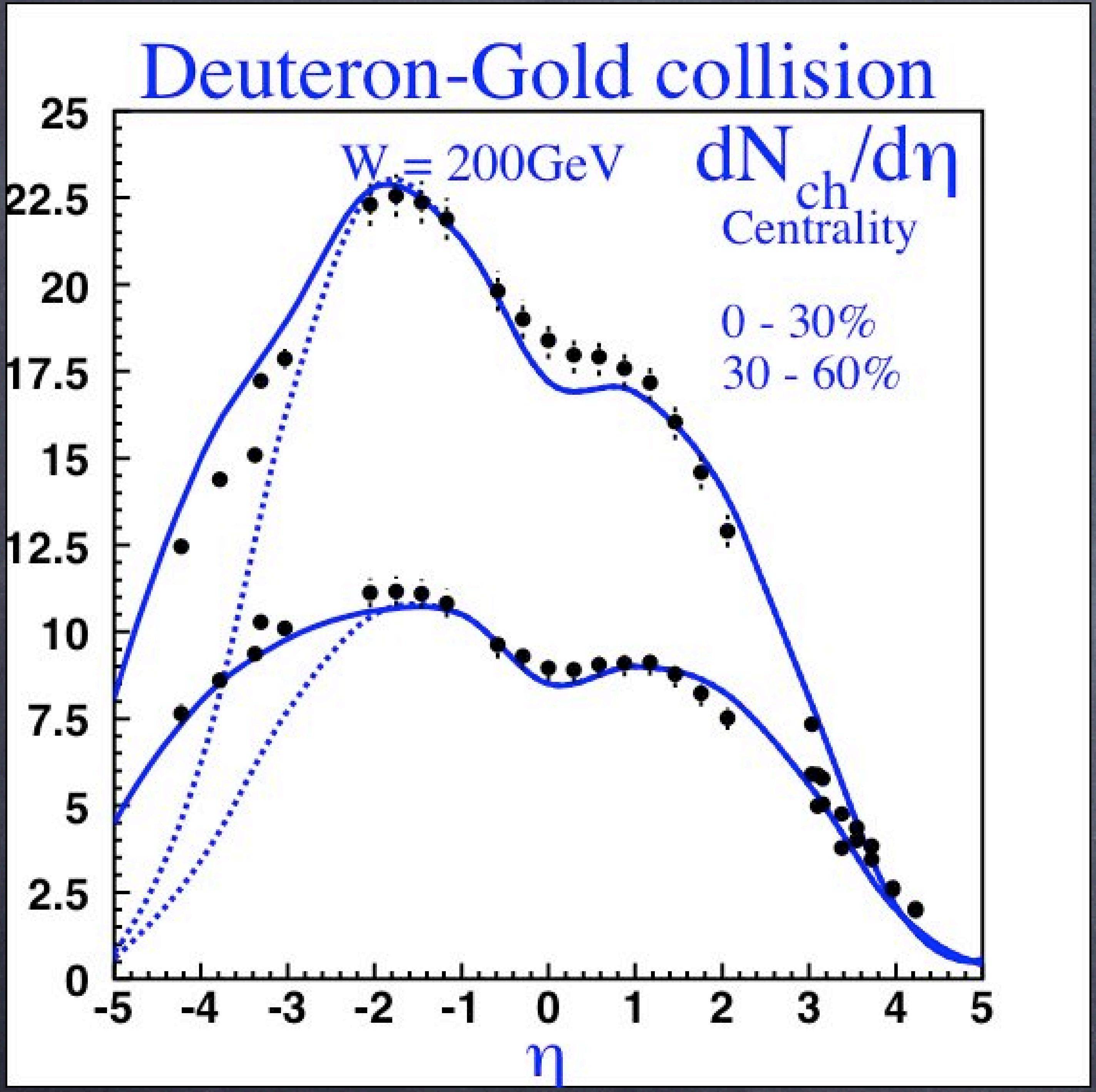
Is x small enough to generate quantum evolution?

- CGC resums higher twists and evolution logarithms at $x<<1$. Requires modeling to match onto $x\sim1$, $Q\rightarrow\infty$ physics.

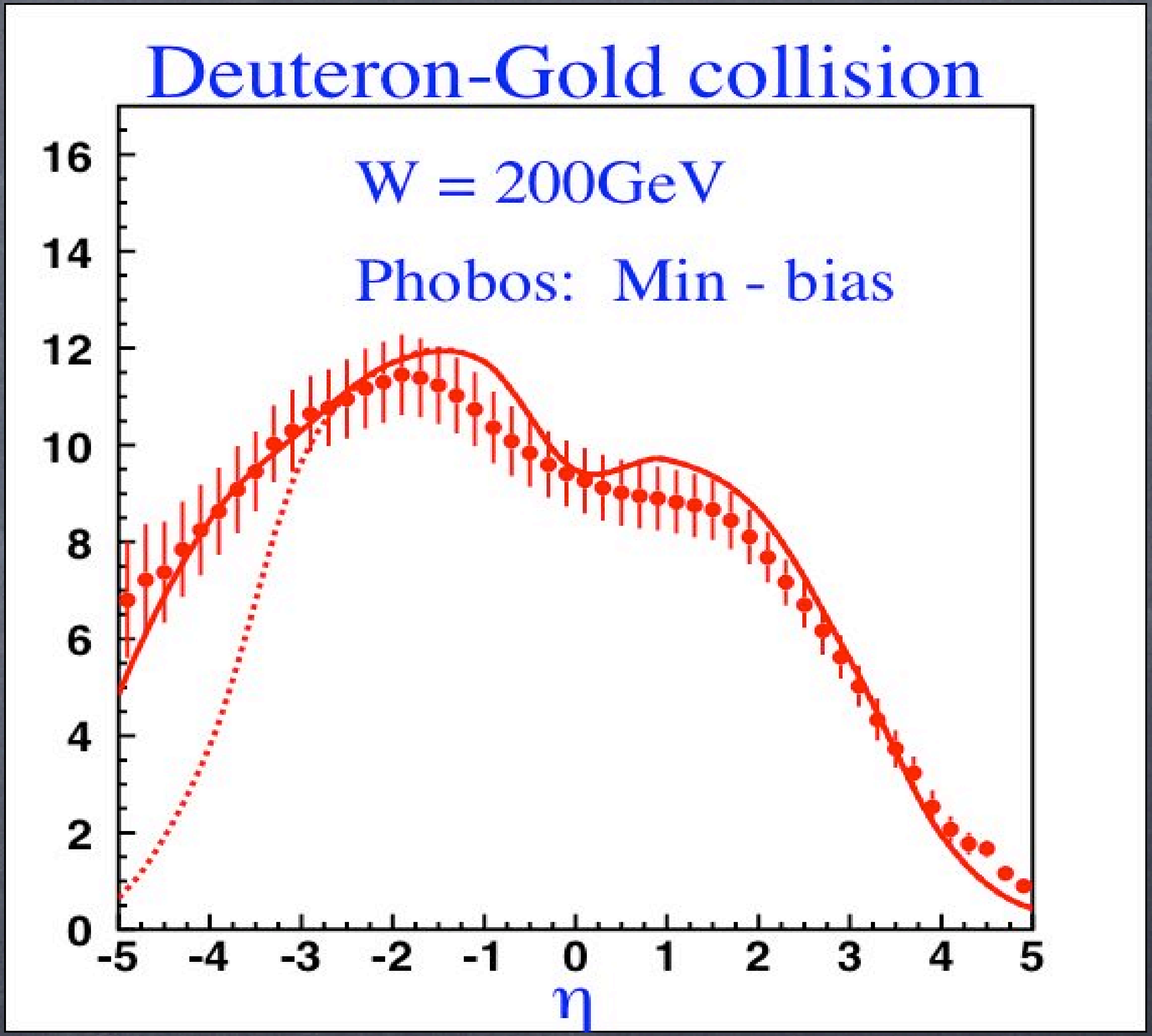
- Shadowing models take into account only one high parton density effect at a time but match well onto $x\sim1$, $Q\rightarrow\infty$.

Hadron multiplicities in dAu at RHIC

- Total multiplicities (Kharzeev, Levin, Nardi)

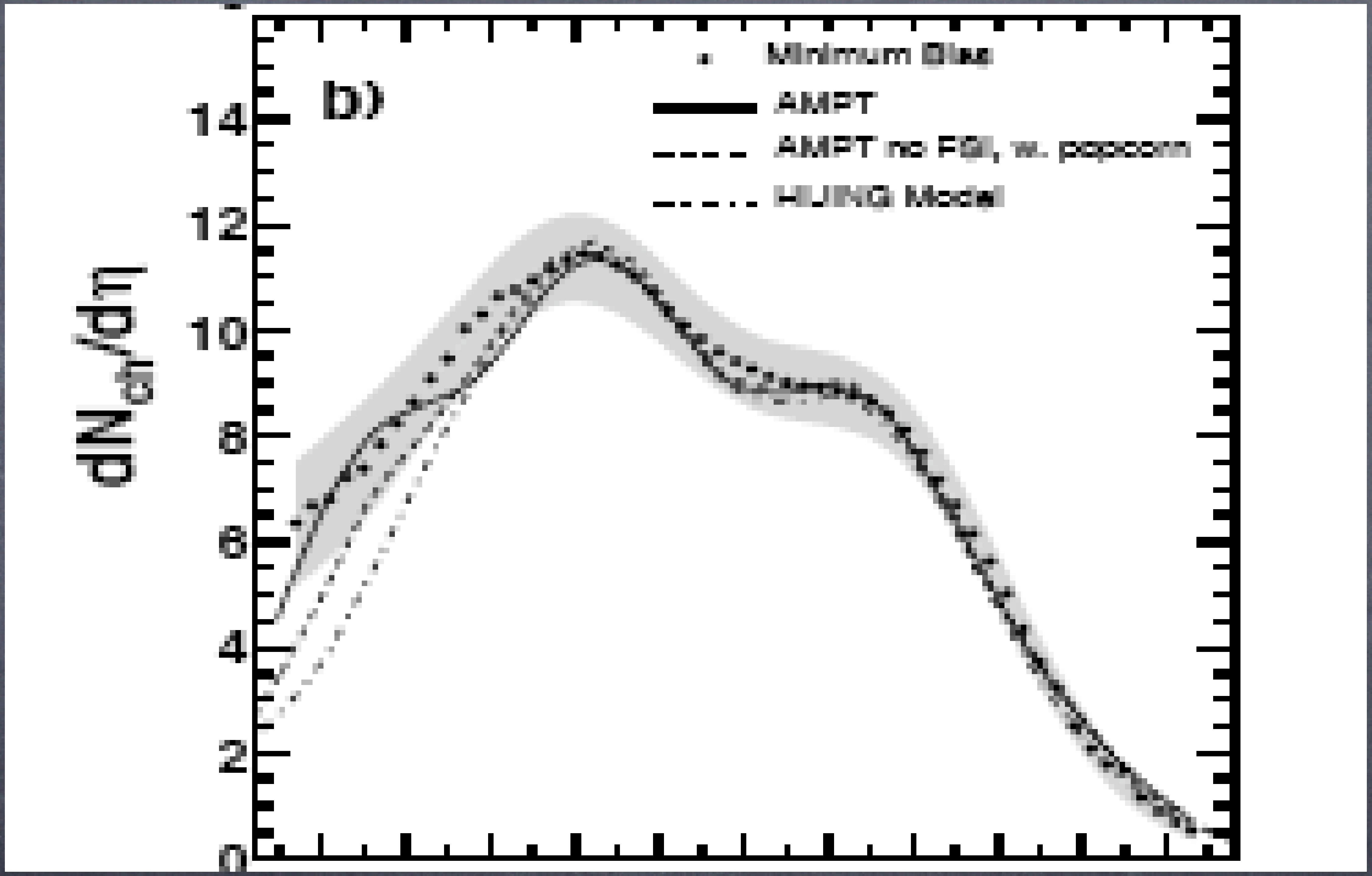


BRAHMS



PHOBOS

Multiplicity by other models



by PHOBOS

Pseudo-rapidity asymmetry

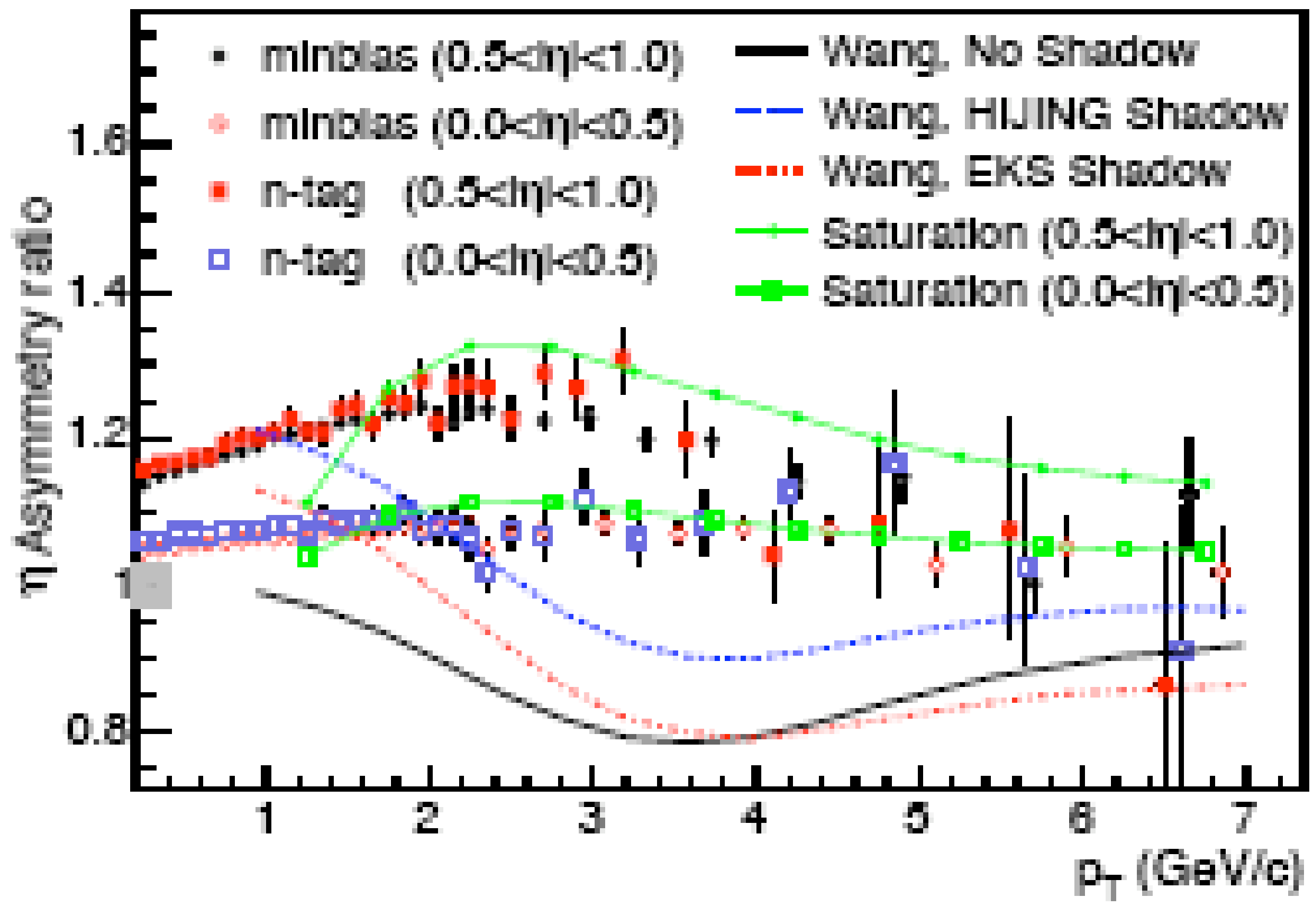


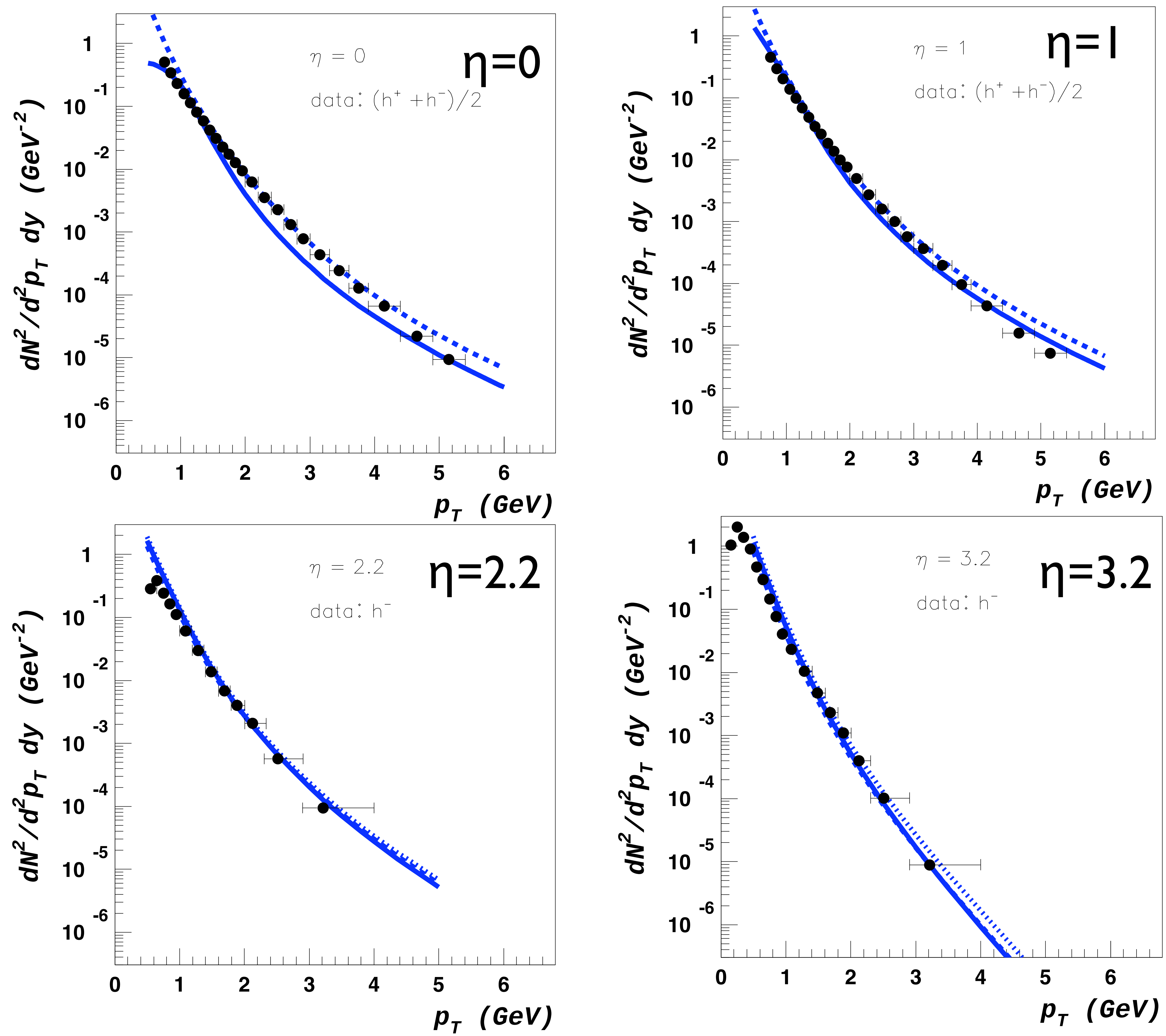
FIG. 3: (Color online) The ratio of charged hadron spectra in the backward rapidity to forward rapidity region for minimum bias and ZDC-d neutron-tagged events. Calculations based on pQCD [3] ($y{=}-1/y{=}1$) for minimum bias events are also shown for cases with no shadowing (solid curve), HIJING shadowing (dashed curve), and EKS shadowing (dot-dashed curve). Calculations in a gluon saturation model [13] for minimum bias events are shown for $0.5 < |\eta| < 1.0$ (filled circles with solid line) and for $0.0 < |\eta| < 0.5$ (open squares with solid line).

by STAR

Hadron spectra in dAu

Kharzeev, Kovchegov, KT

data by BRAHMS

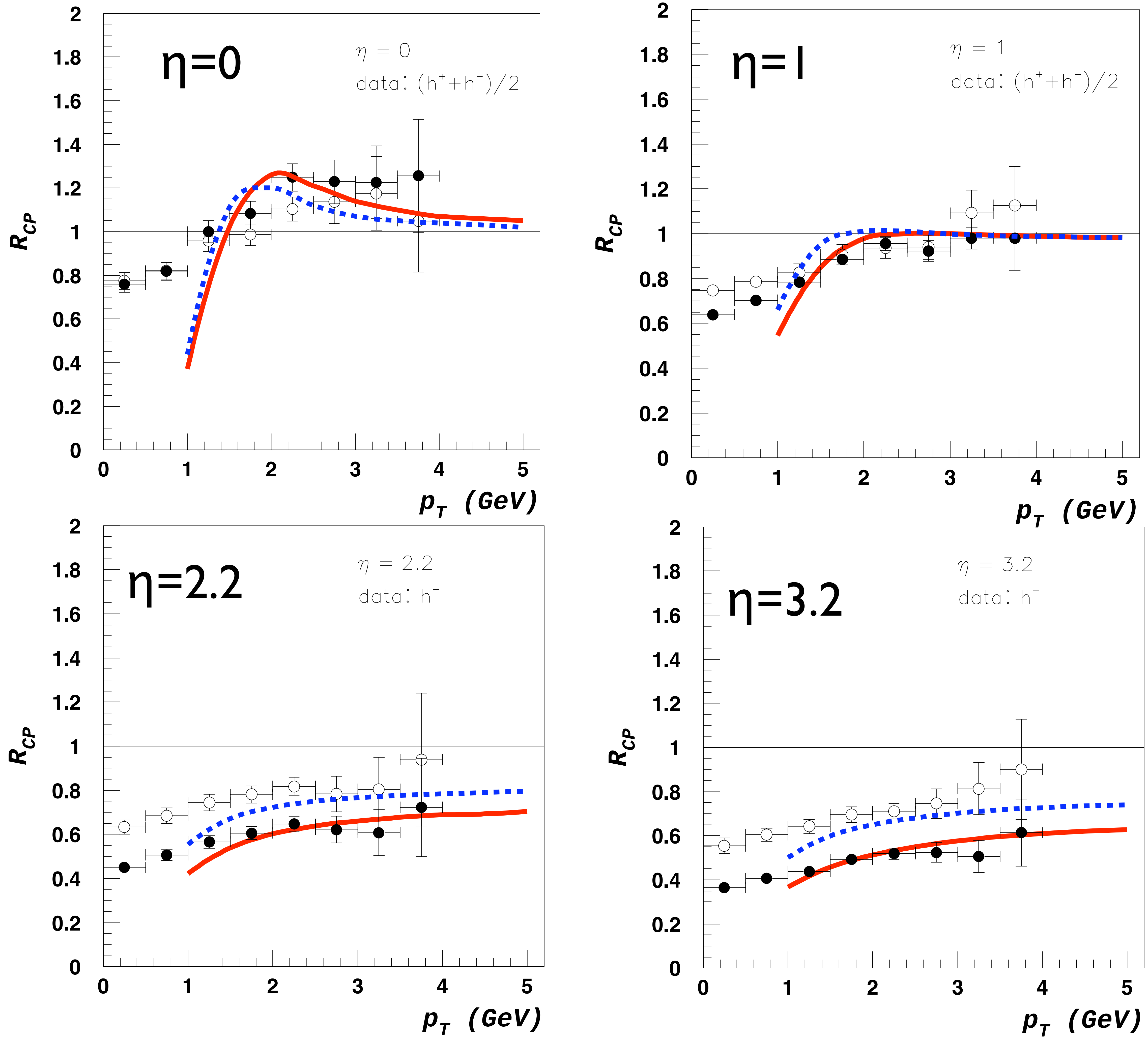


Hadron spectra in dAu

Kharzeev, Kovchegov, KT

data by BRAHMS

see also Baier, Kovner, Wiedemann



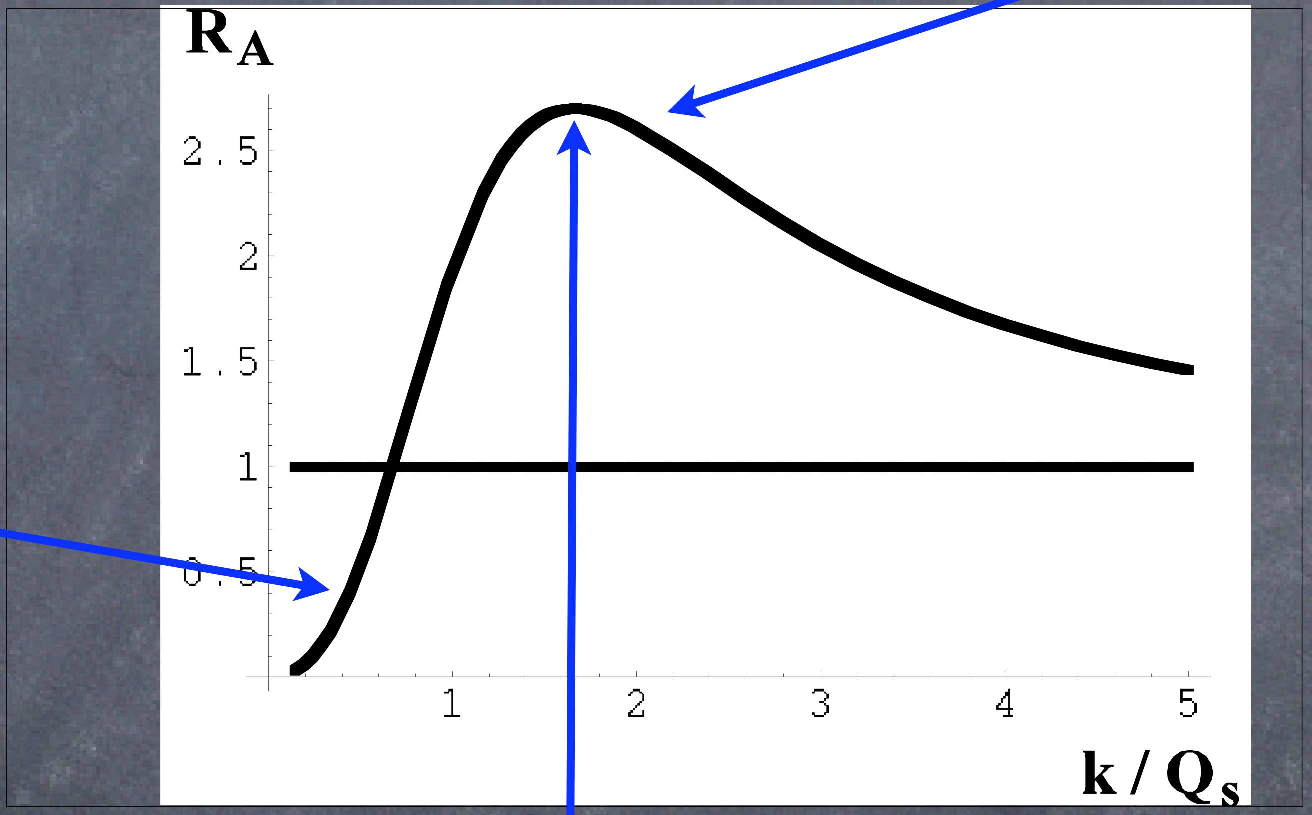
Physics behind Cronin and suppression

Kharzeev, Kovchegov, KT

- In a quasi-classical approximation Cronin enhancement appears due to multiple rescattering of partons in nucleus.

Anti-Shadowing

Shadowing: small k, small x



Most gluons are here

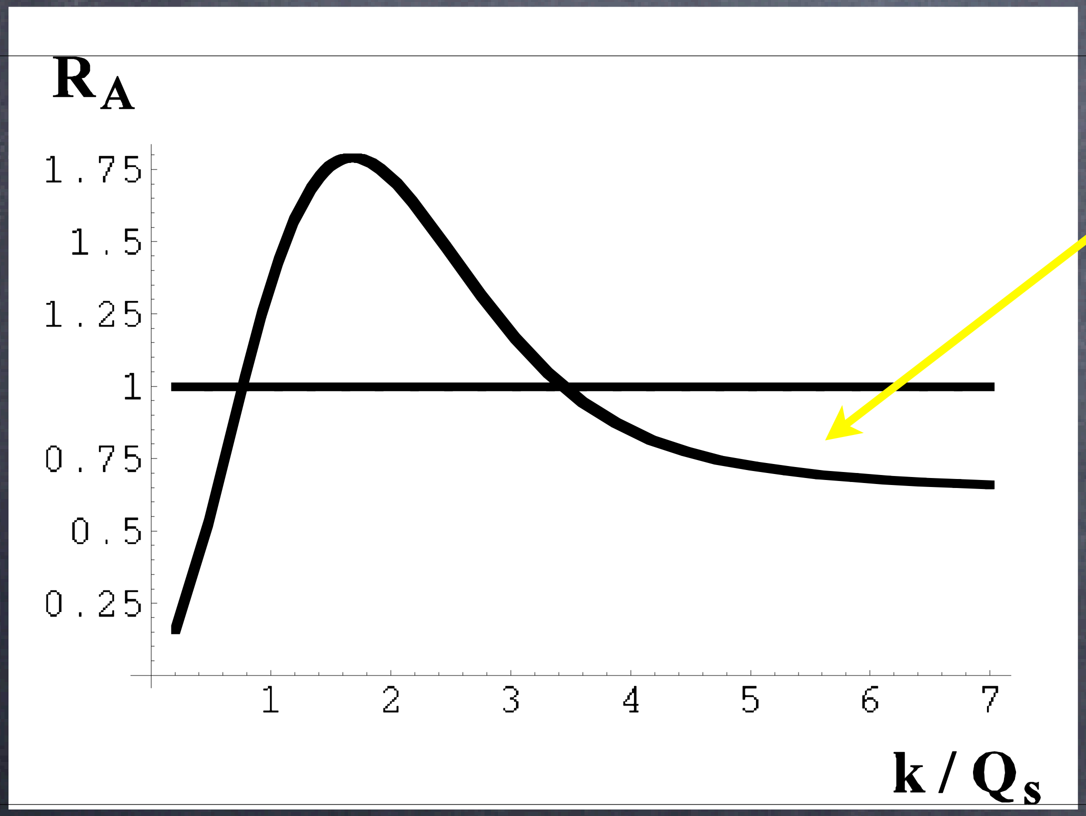
see also Baier, Kovner, Wiedamann; Blaizot, Gelis, Venugopalan; Iancu, Itakura, Triantafyllopoulos

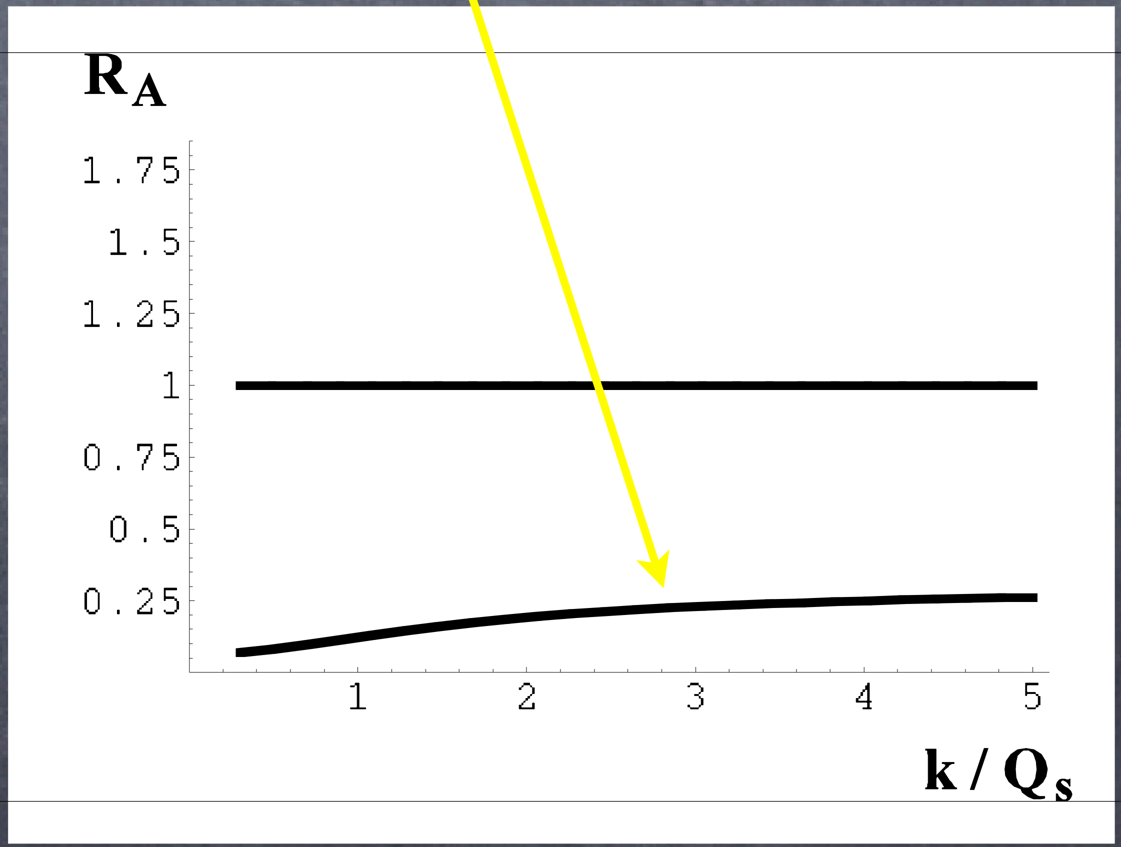
- Gluons are redistributed from low to high k_T

Physics behind Cronin and suppression

- Due to the non-linear evolution effects at high energies/forward rapidities (low x) gluons in dA get stronger suppressed than in pp.

$$\phi(\underline{k}, y) \sim \left(\frac{Q_s^2}{\underline{k}^2}\right)^{\gamma} \qquad \gamma \approx \frac{1}{2} \quad \Rightarrow \quad \phi \propto A^{1/6} \quad \textbf{instead of} \quad A^{1/3}$$





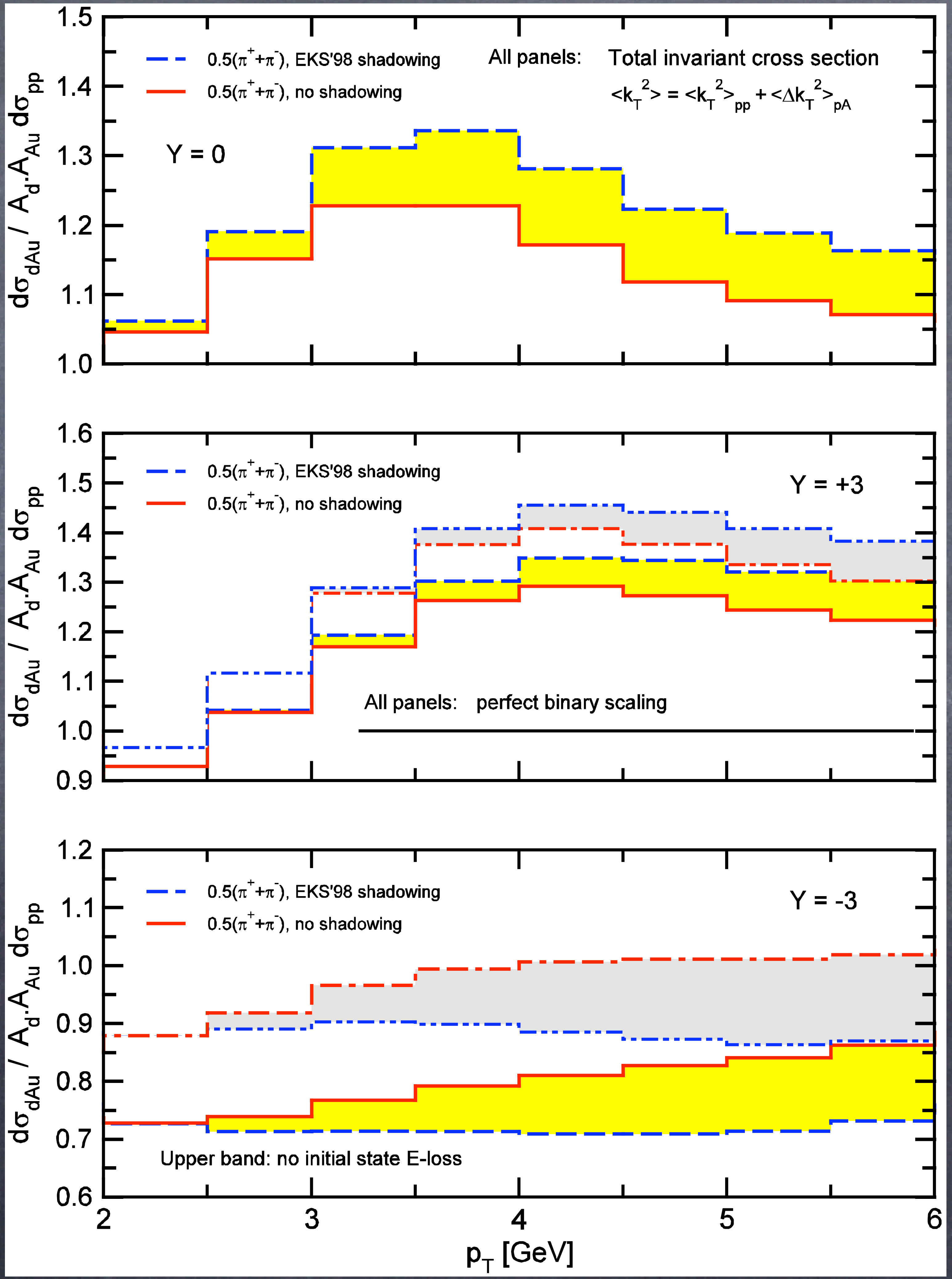
Kharzeev, Levin, McLerran

Kharzeev, Kovchegov, KT

see also Baier, Kovner, Wiedamann; Blaizot, Gelis, Venugopalan; Iancu, Itakura, Triantafyllopoulos

Other models

Gyulassy, Vitev, Wang, Zhang



Fragmentation effect?

Fragmentation effect due to large x_1 does not depend on energy while the saturation effect does ⇒

Increase dAu energy to verify

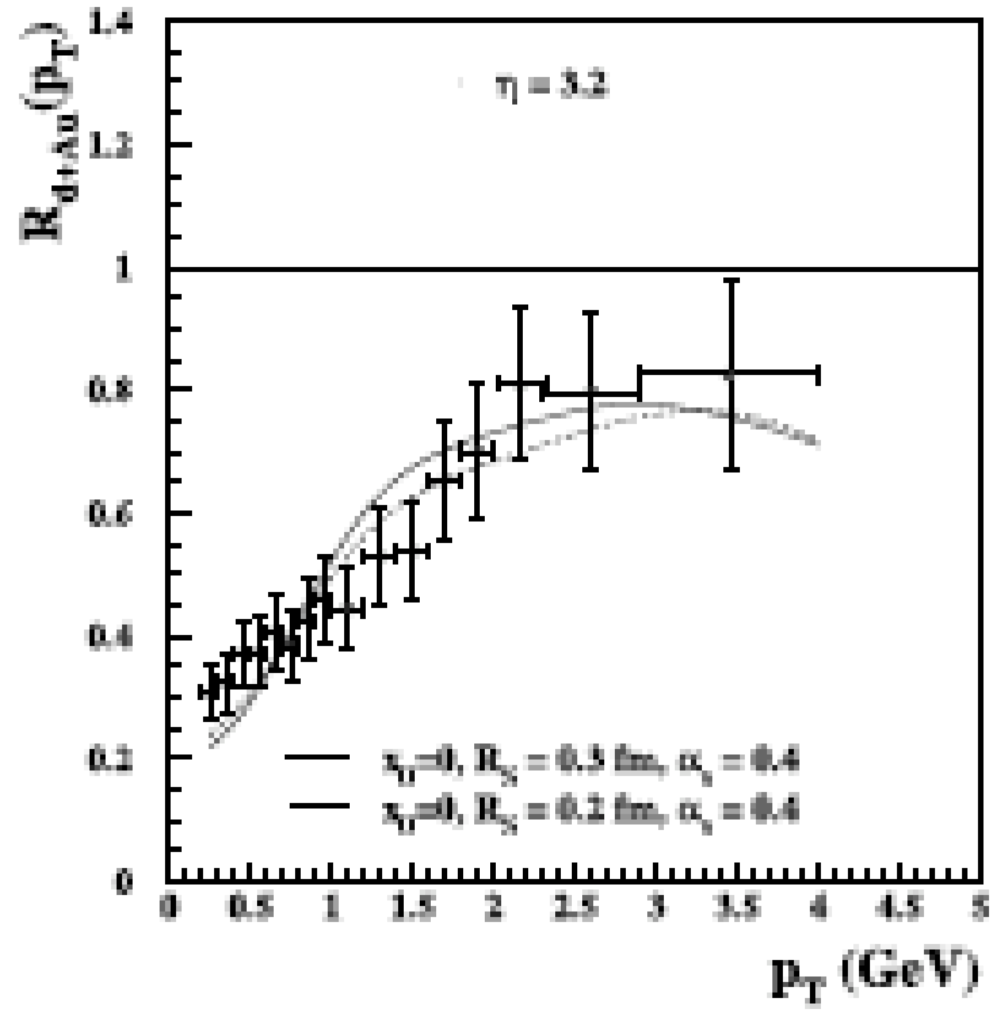
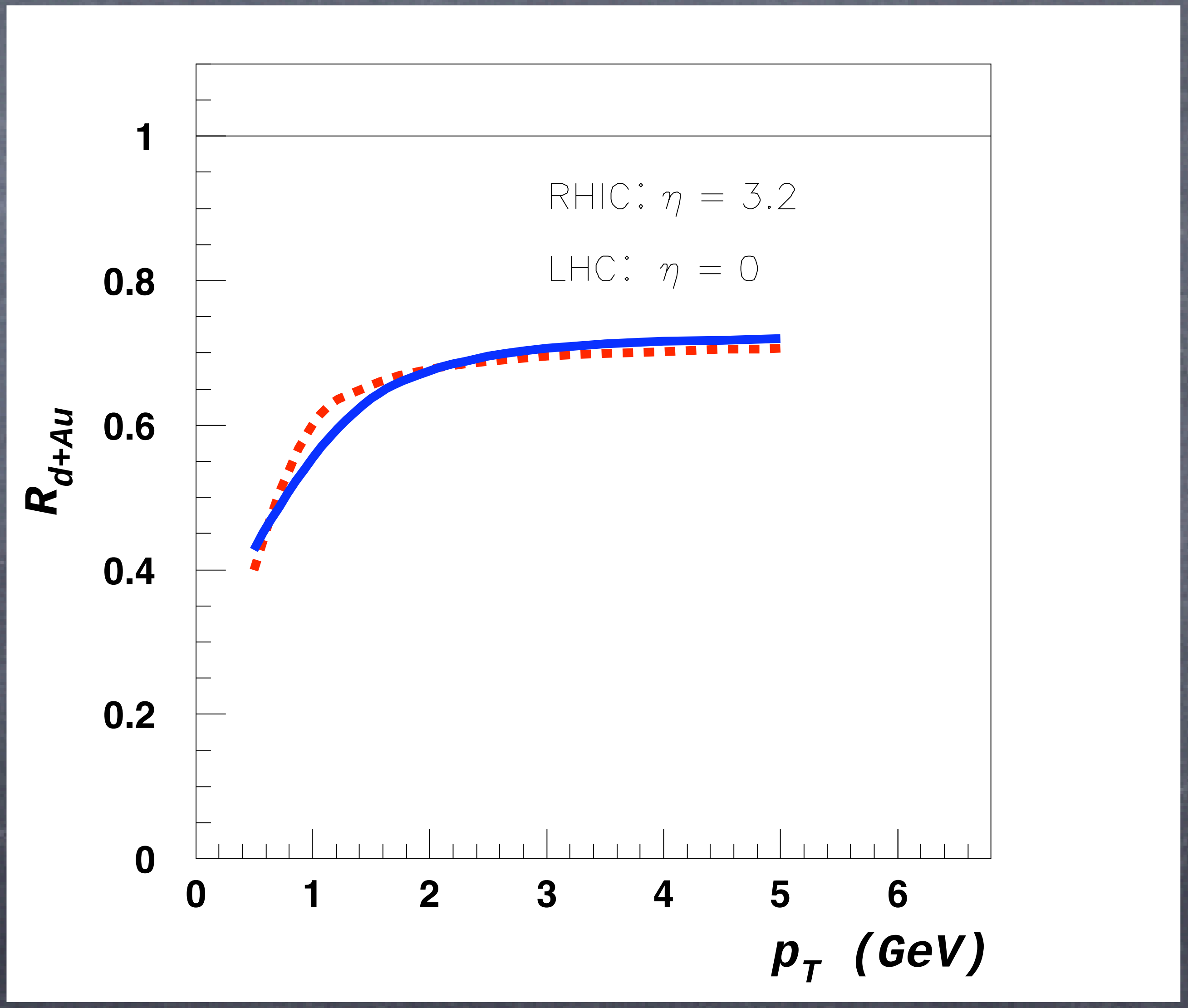


FIG. 3: Ratio of negative particles production rates in $d-Au$ and pp collisions as function of p_T. Data are from [1], solid and dashed curves correspond to calculations with the diquark size 0.3 fm and 0.4 fm respectively.

Kopeliovich et al

pA at LHC

- Midrapidity at LHC looks similar to y≈3 at RHIC.

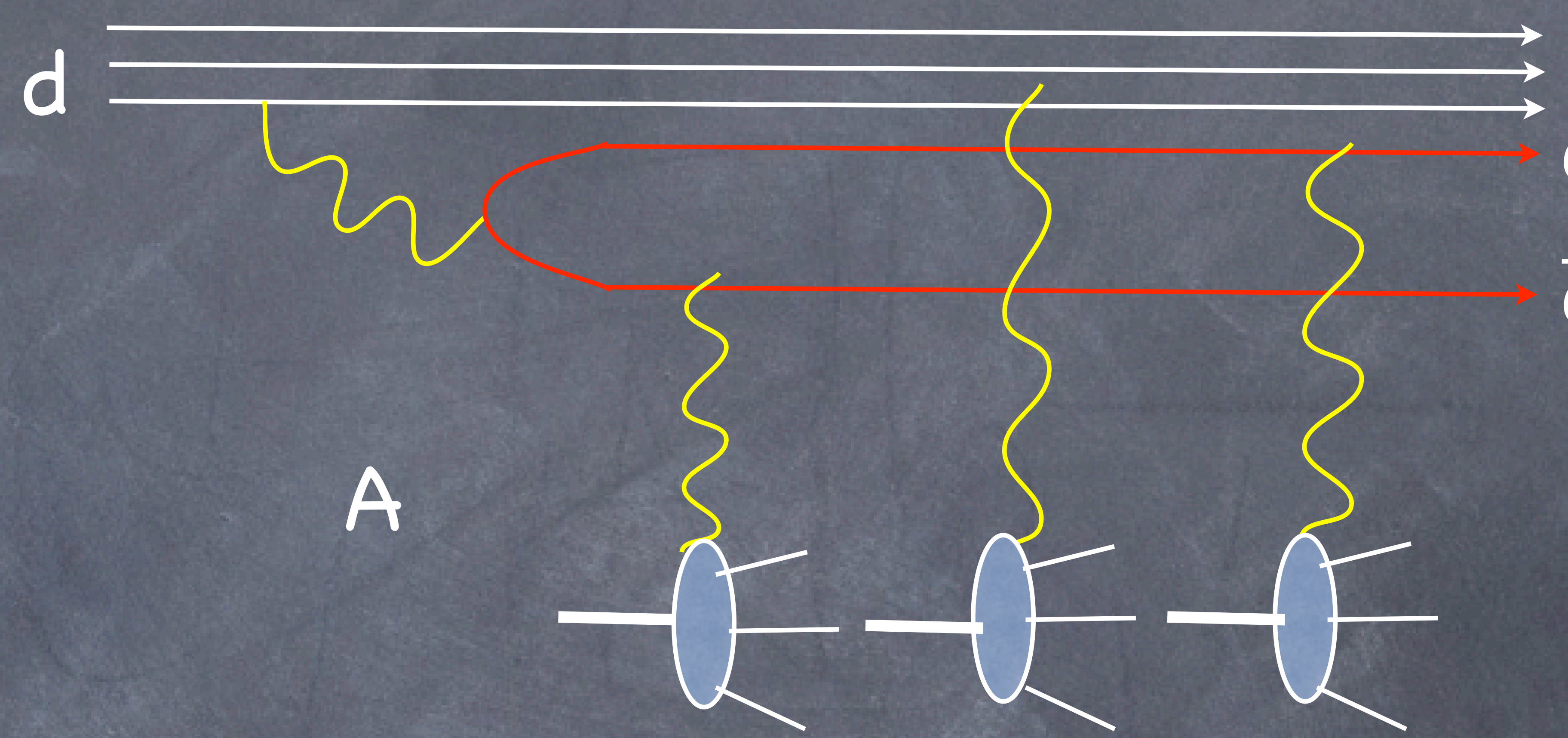


Heavy Quark Production in pA collisions

- coherence length of qq pair

$$l_c \approx \frac{E_g}{(2m_q)^2} = \frac{1}{2M_N x_2}$$

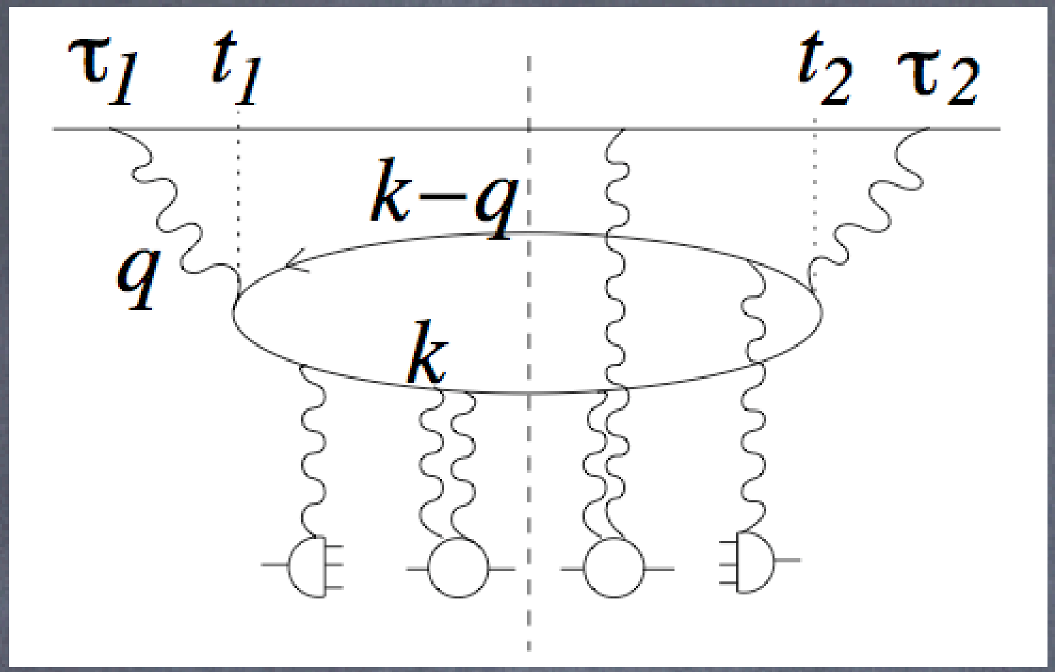
where $x_2 = \frac{m_T}{\sqrt{s}} e^{-y}$

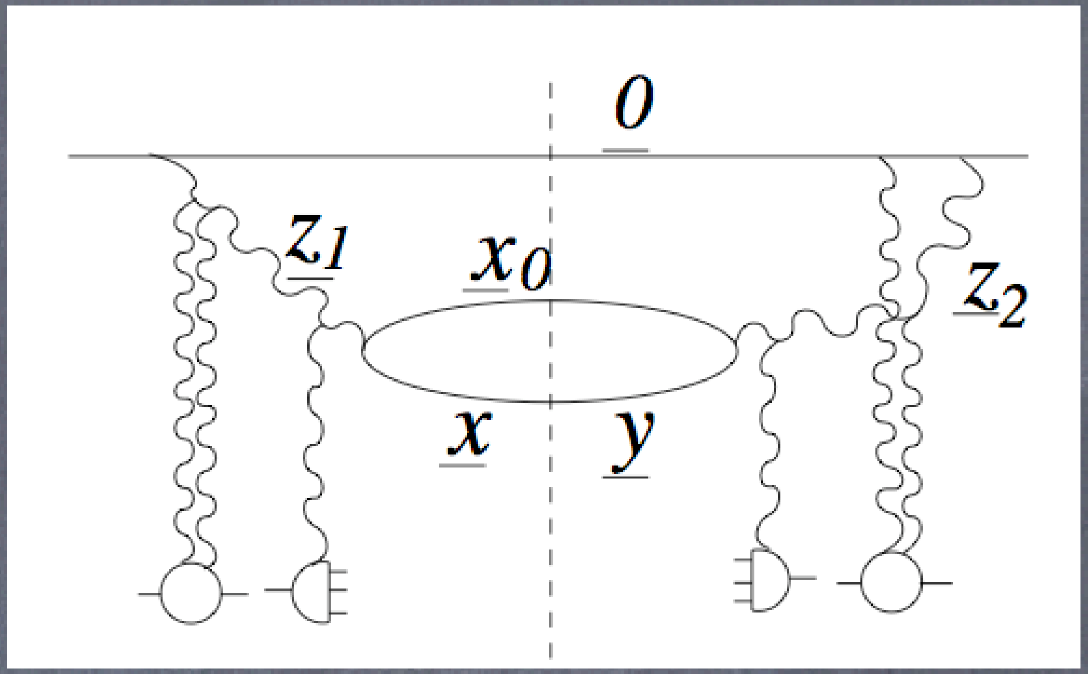


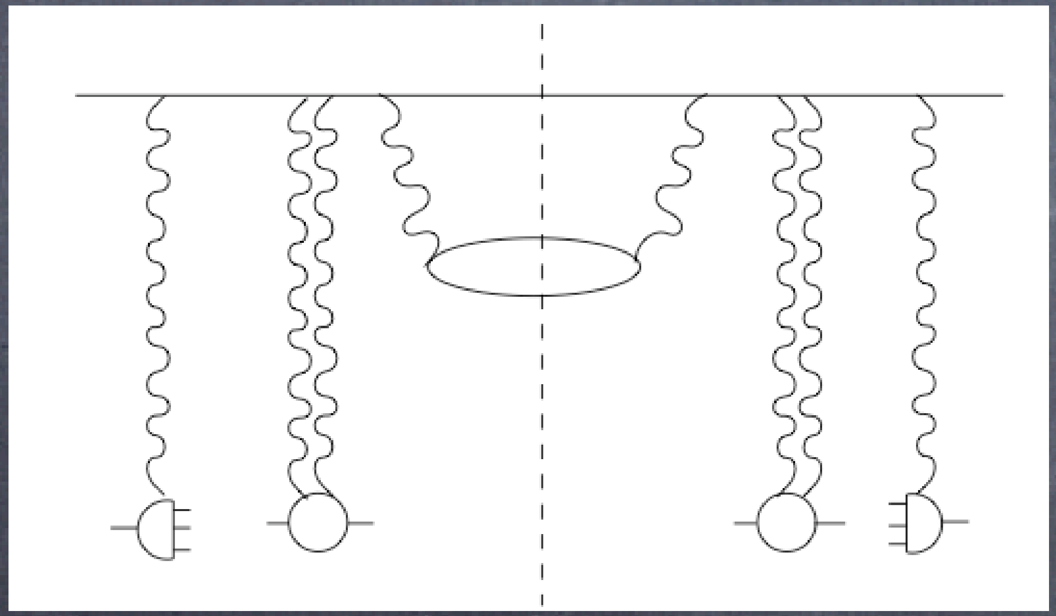
- For charm at RHIC $l_c = 15e^y \,\mathrm{fm}$

- At forward rapidity $l_c \gg R_A$

Initial vs final state interactions







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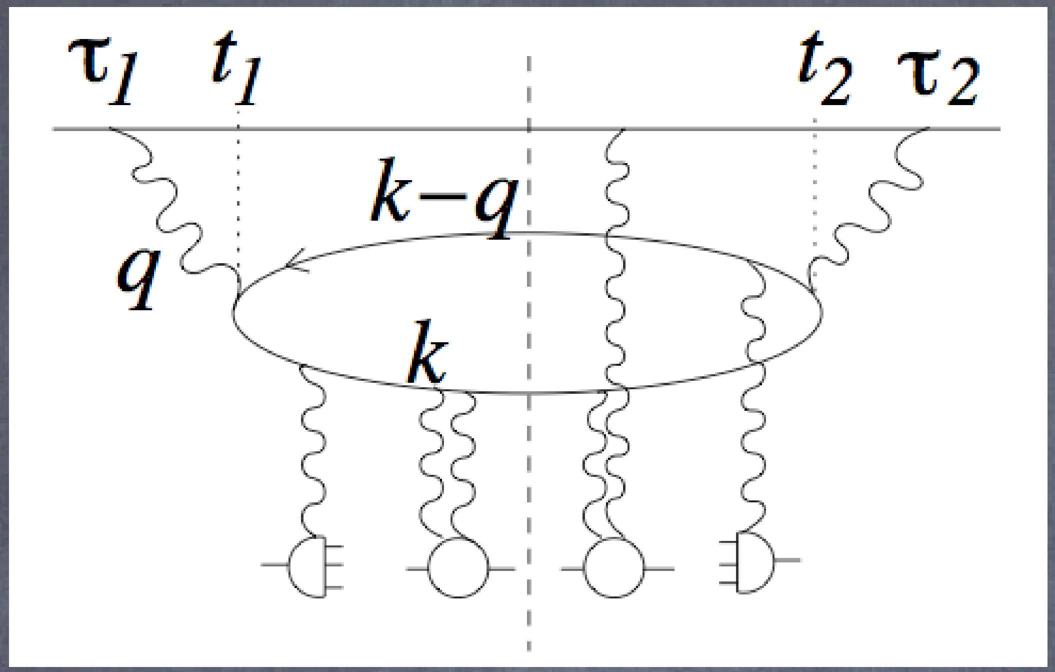
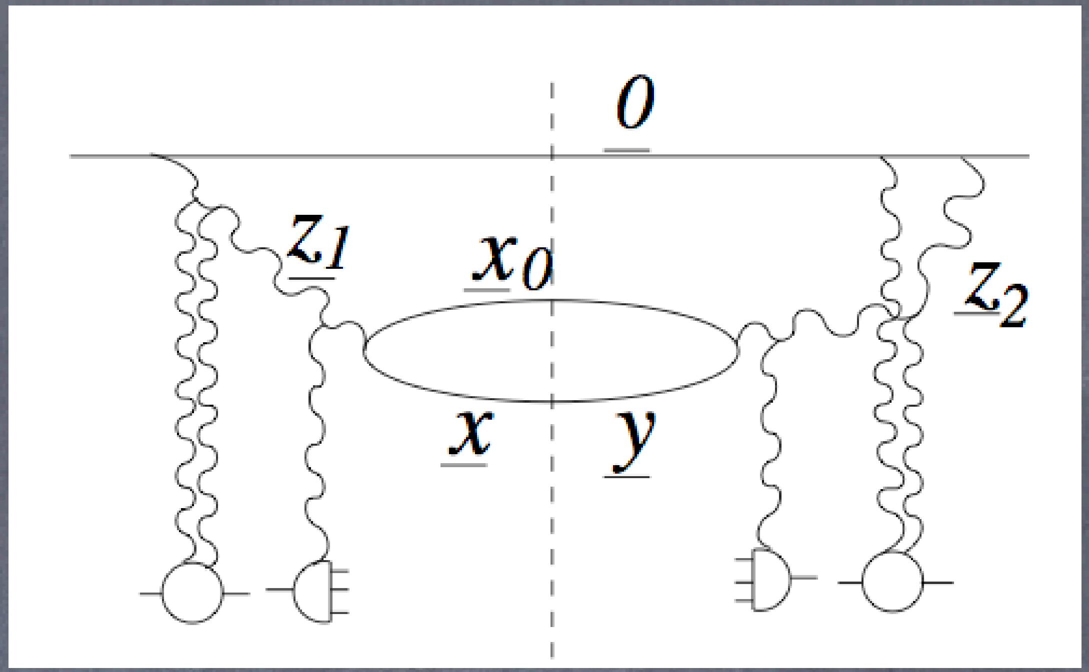
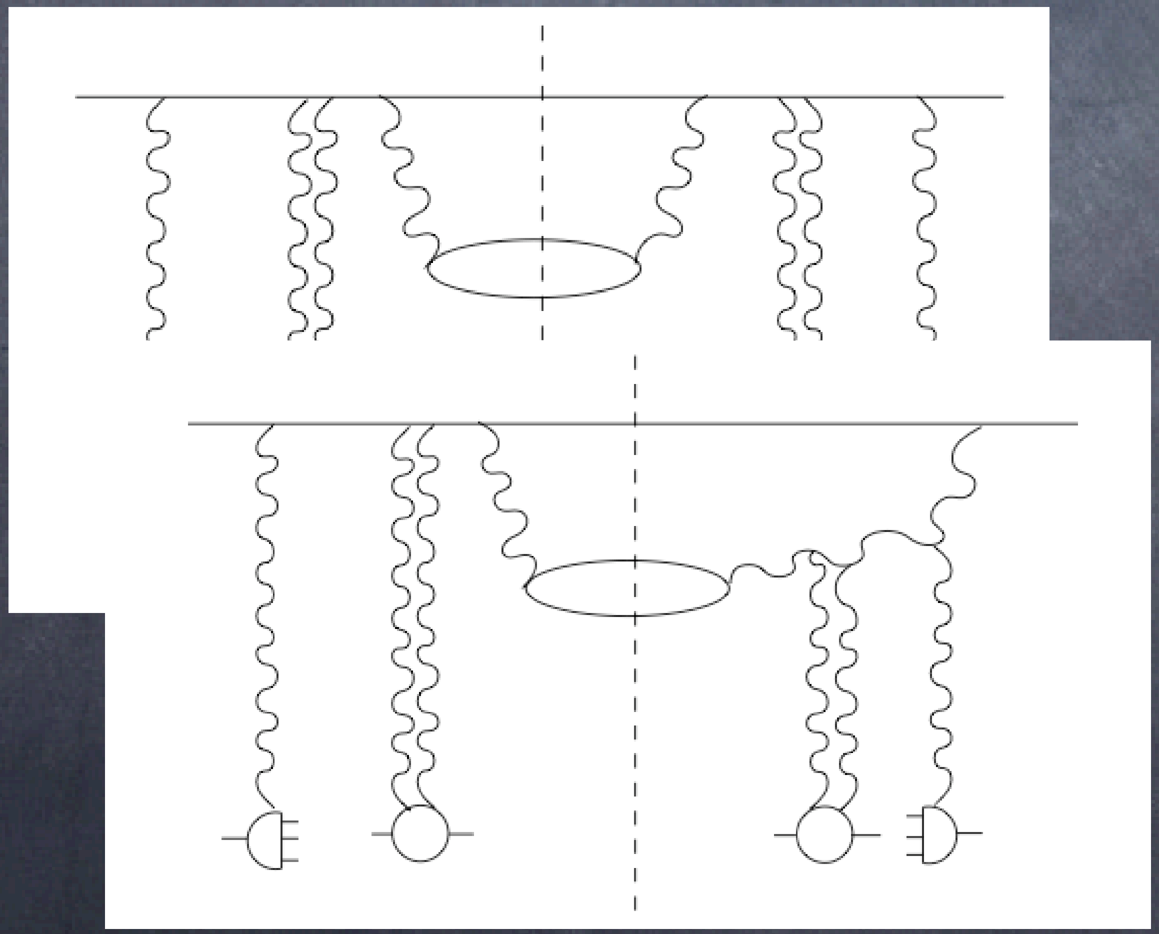
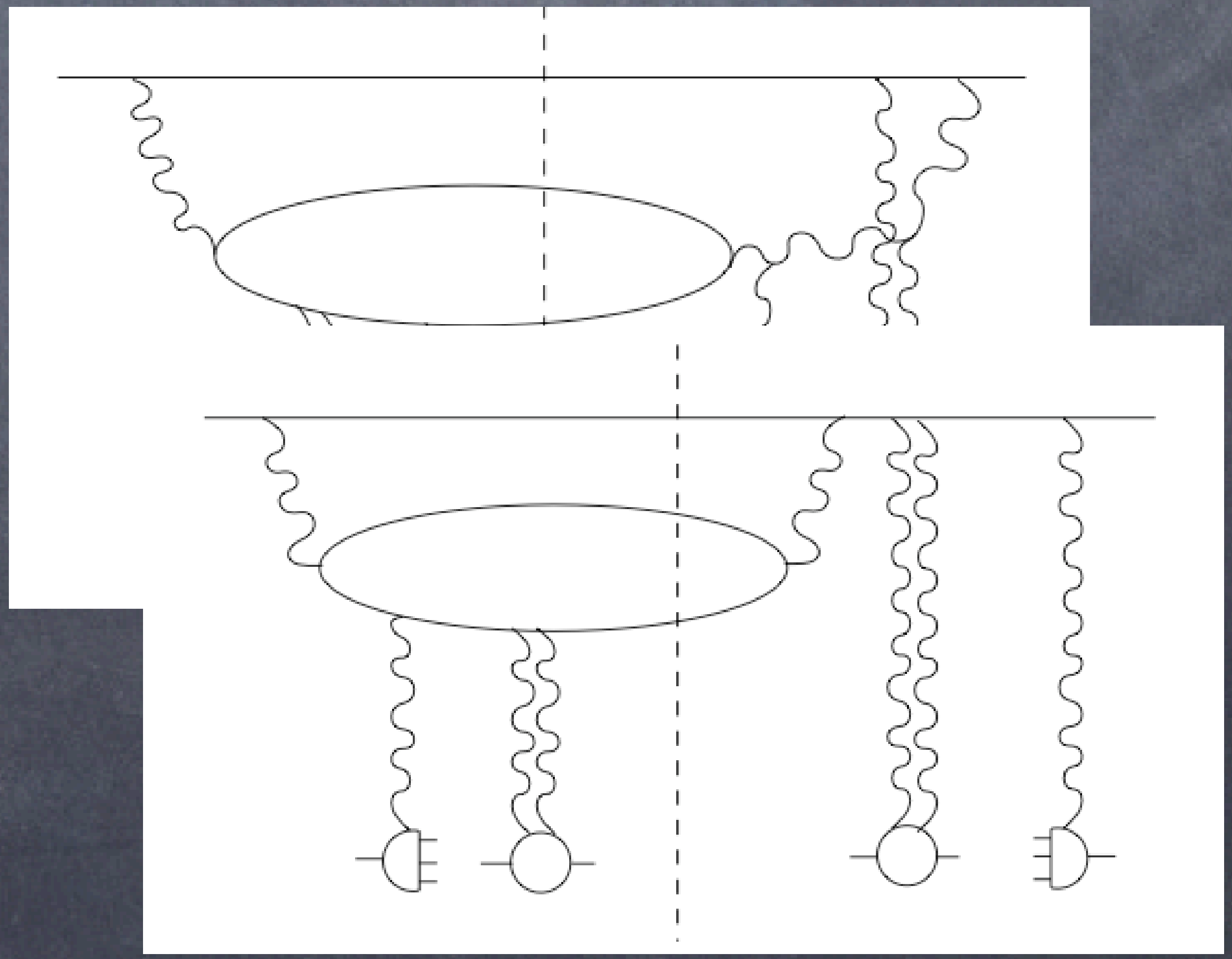


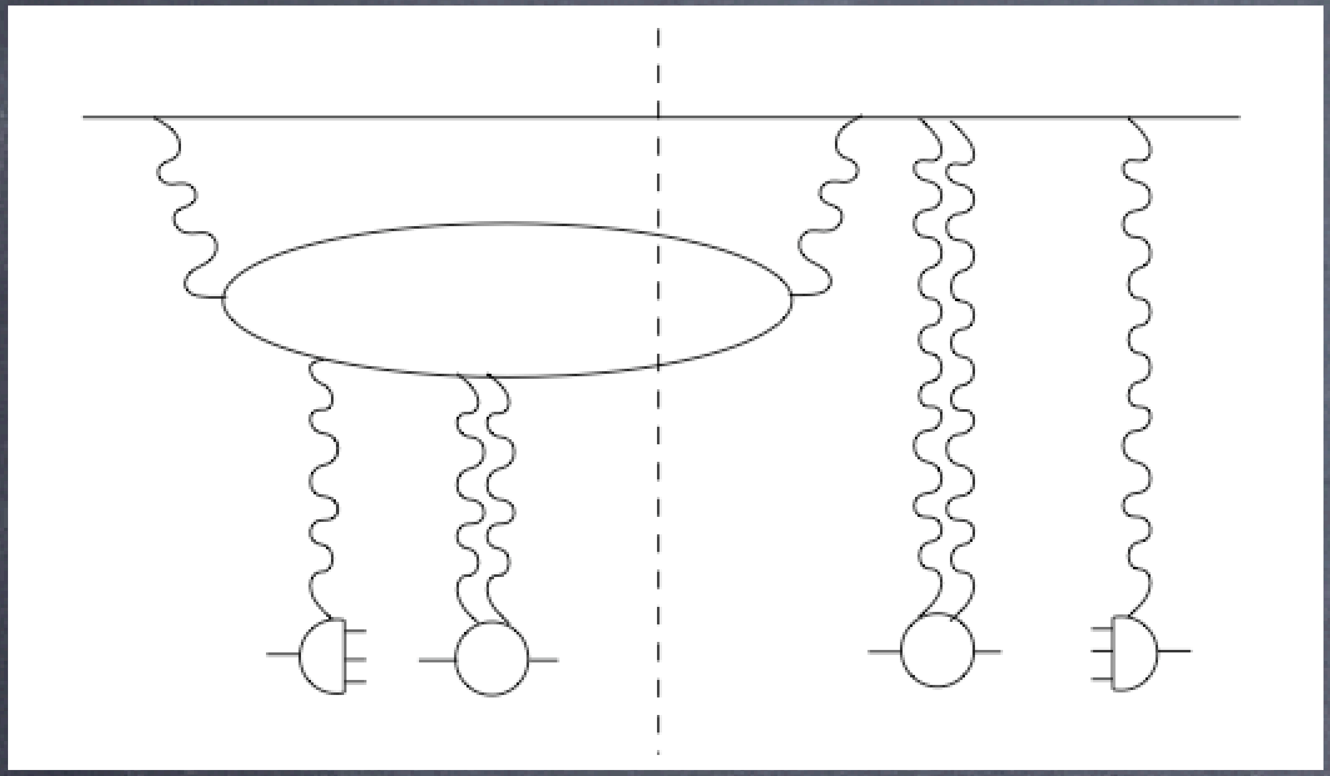


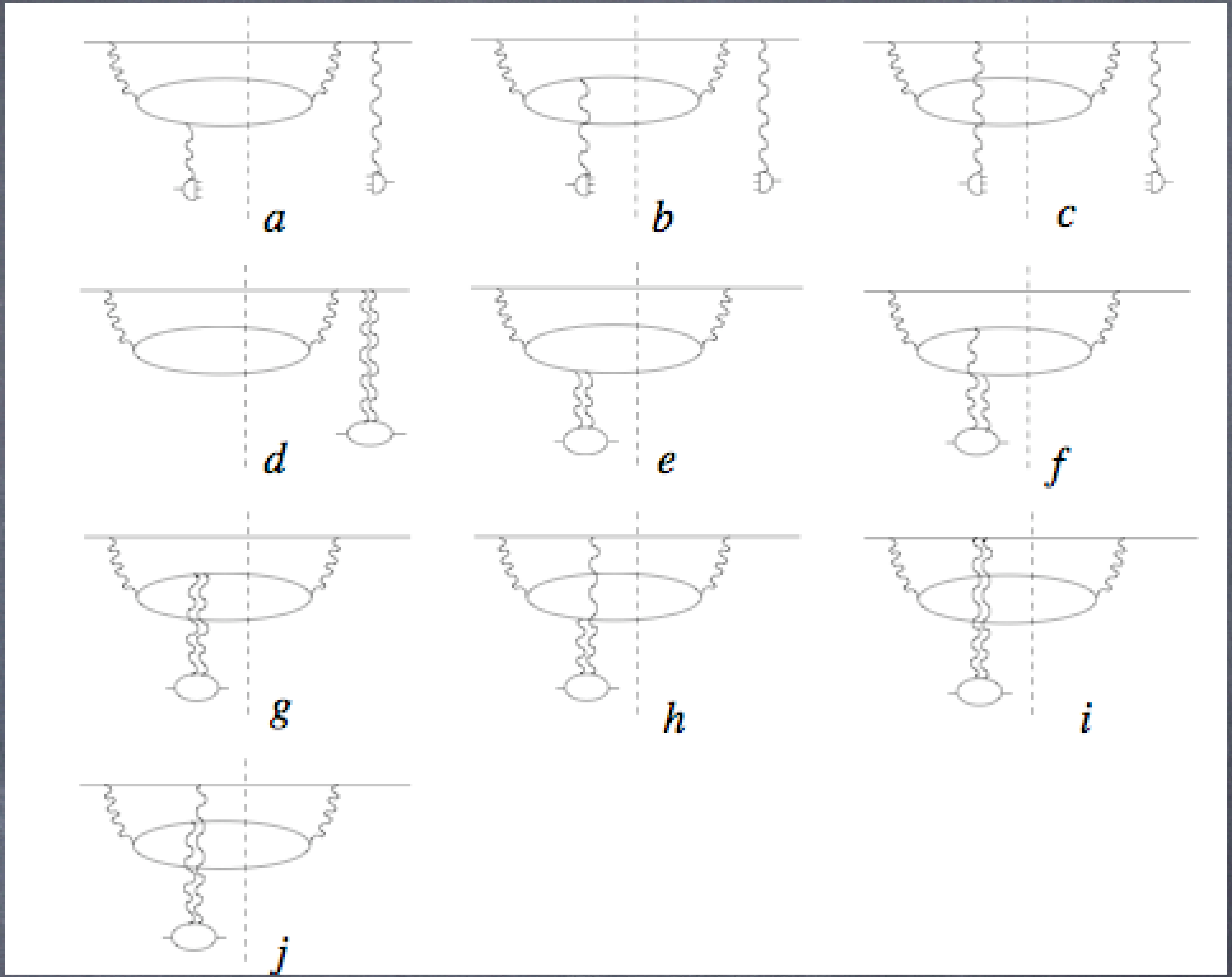




Dipole-nucleus interactions

- Quasi-classical approximation:





$$-P(\underline{x}, \underline{x}_0) = -\frac{1}{8}\underline{x}^2 Q_s^2 - \frac{1}{8}\underline{x}_0^2 Q_s^2 + \frac{1}{8N_c^2}(\underline{x} - \underline{x}_0)^2 Q_s^2$$

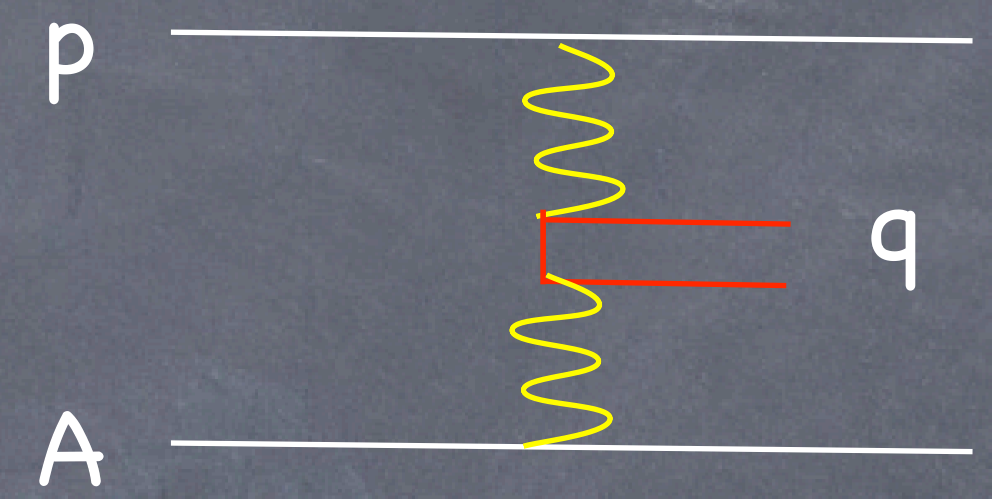
$$Q_s^2 = \frac{2\pi^2 \alpha_s N_c}{C_F} \rho T(\underline{b}) x G(x, 1/\underline{x}^2)$$

see also

Kopeliovich, Tarasov

Single inclusive quark x-section

KT;
Kovchegov, KT



Size of the initial dipole

Number of dipoles in proton

Total rapidity Quark rapidity

$$\frac{d\sigma}{d^2k\,dy_1\,dy_2}(z_{01}) = \frac{1}{2(2\pi)^4}\int d^2z_0' d^2z_1' n_1(\underline{z}_0,\underline{z}_1;\underline{z}_0',\underline{z}_1';Y-y)\, d^2x_1 d^2x_2 d^2y_1 e^{-i\underline{k}\cdot(\underline{x}_1-\underline{y}_1)}$$

$$\times \int_0^1 d\alpha \sum_{i,j=1}^{3}\sum_{k,l=0}^{1} (-1)^{k+l}\, \Phi_{ij}(\underline{x}_1-\underline{z}_k,\underline{x}_2-\underline{z}_k;\underline{y}_1-\underline{z}_l,\underline{x}_2-\underline{z}_l;\alpha)\; \Xi_{ij}(\underline{x}_1,\underline{x}_2,\underline{z}_k;\underline{y}_1,\underline{x}_2,\underline{z}_l;\alpha,y)$$

qq wave functions for different time orderings

Rescattering factors

see also Blaizot, Gelis, Venugopalan

Aligned jet configuration

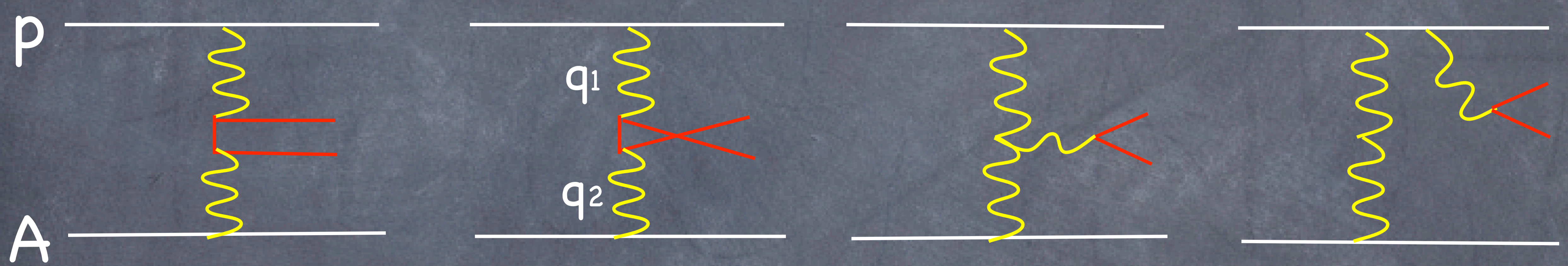
KT

- Assume that quark energy >> anti-quark energy
- Then, $l_c(G) \gg l_c(q\bar{q}) \gg R_A$
- Gluon emission and pair production factorize: the light cone wave function = $\psi_G \otimes \psi_{qq}$
- Although the quark production x-section is quite simple in this case (only 7-dim integral :) it applies only in the situation when q and anti-q are separated by large rapidity gap.
- Exact result: see Kovchegov, KT, 06

k_T-factorization

Levin, Ryskin, Shabelsky, Shuvaev,
Catani, Ciafaloni, Hautmann,
Collins, Ellis All:1991

- kT-factorization assumes that qq production process can be factorized out from the wave functions of proton and nucleus



- Cross section is much easier to calculate

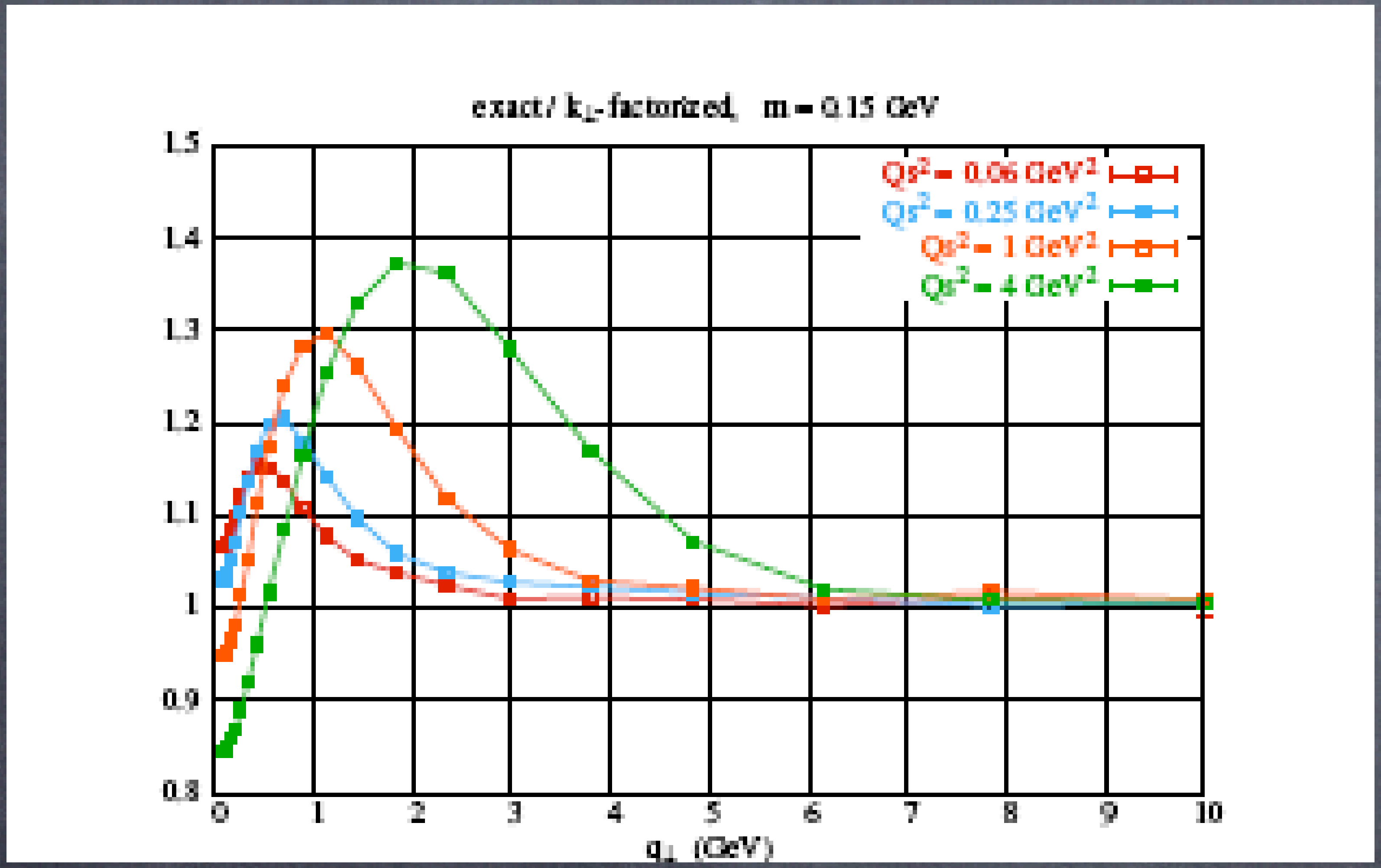
$$\frac{d\sigma}{d^2k\,dy_1dy_2} = \int d^2q_1 \int d^2q_2 \phi_p(\underline{q}_1, y_1)\, A_{gg}(s,t,u,q_1,q_2)\, \phi_A(q_2,y_2)$$

- It was proved for single inclusive gluon production in pA (Kovchegov, K.T.);

How good is k_T-factorization?

Fujii, Gelis, Venugopalan

- Ratio of the BGV result to the k_T-factorization:



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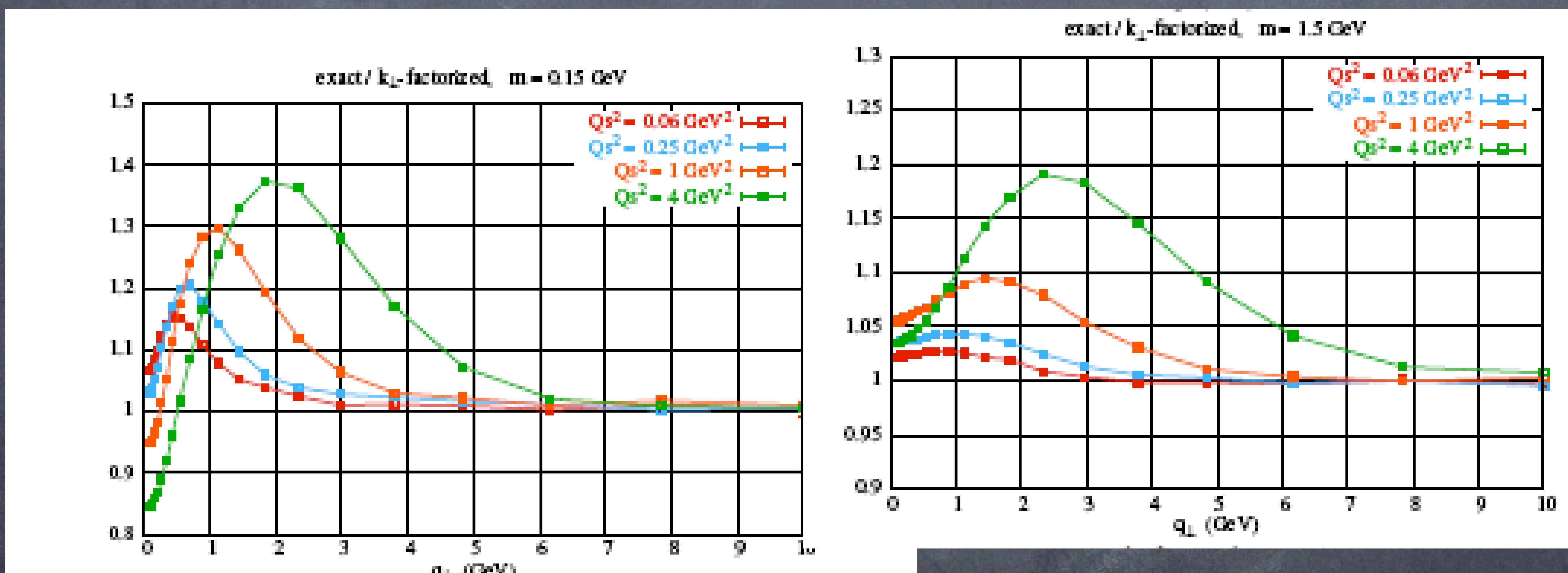

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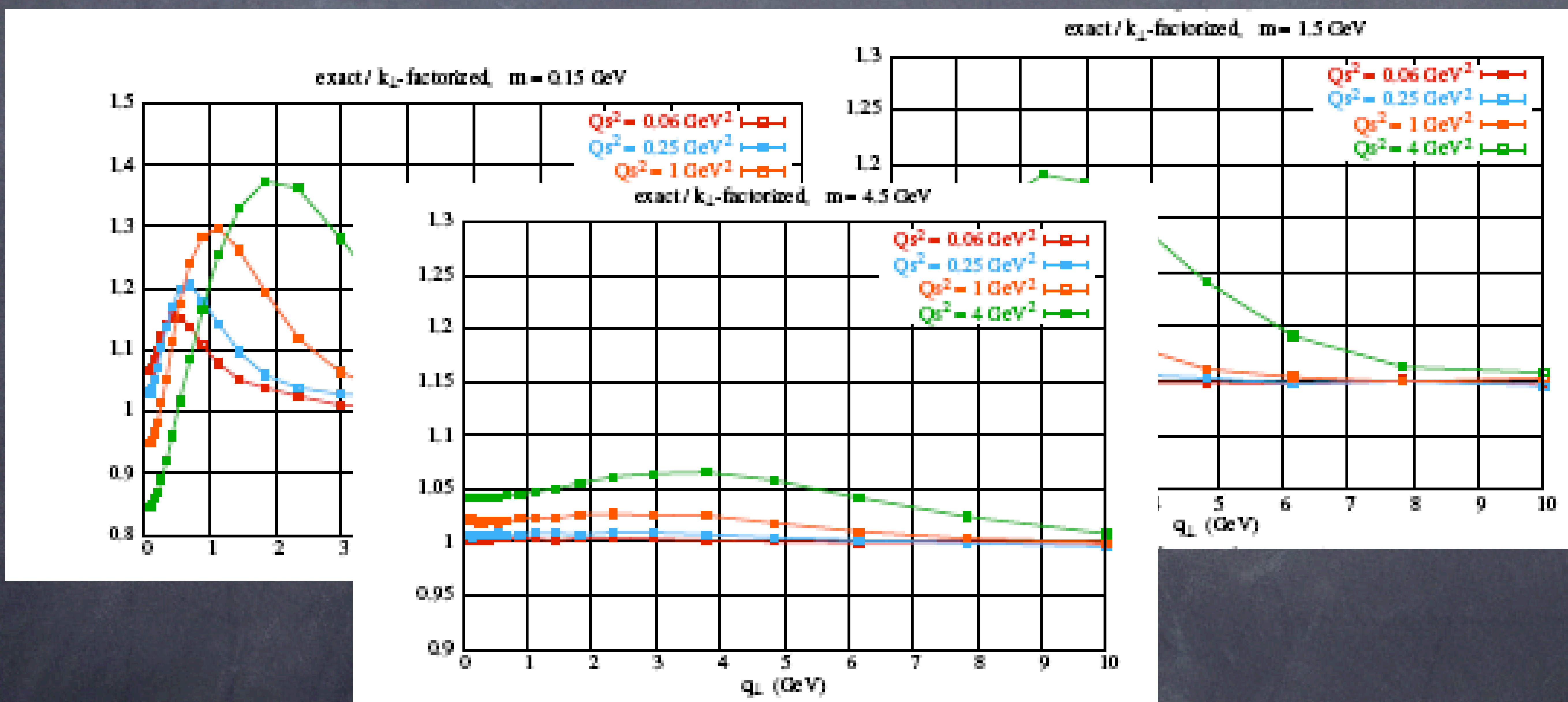
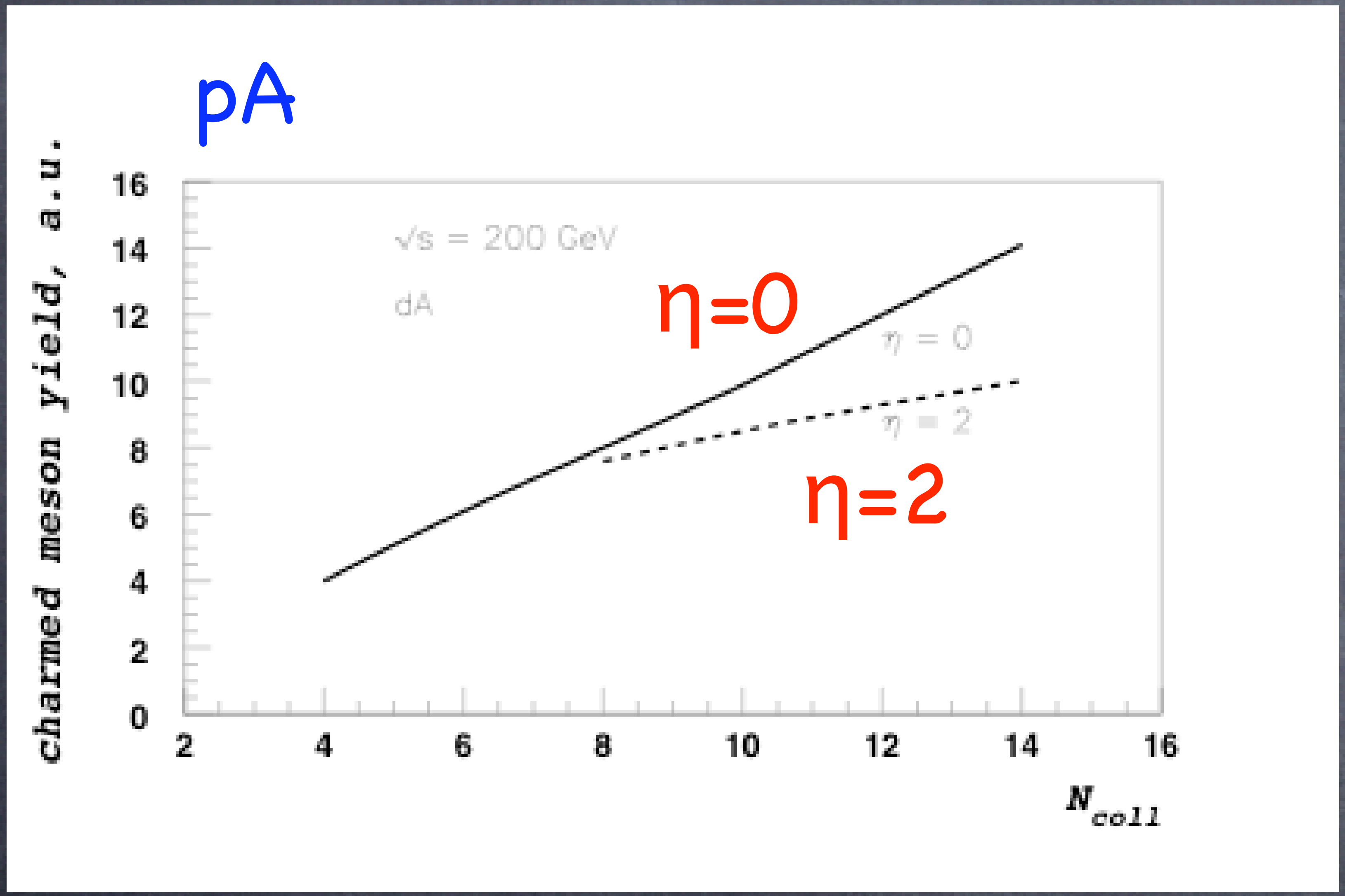
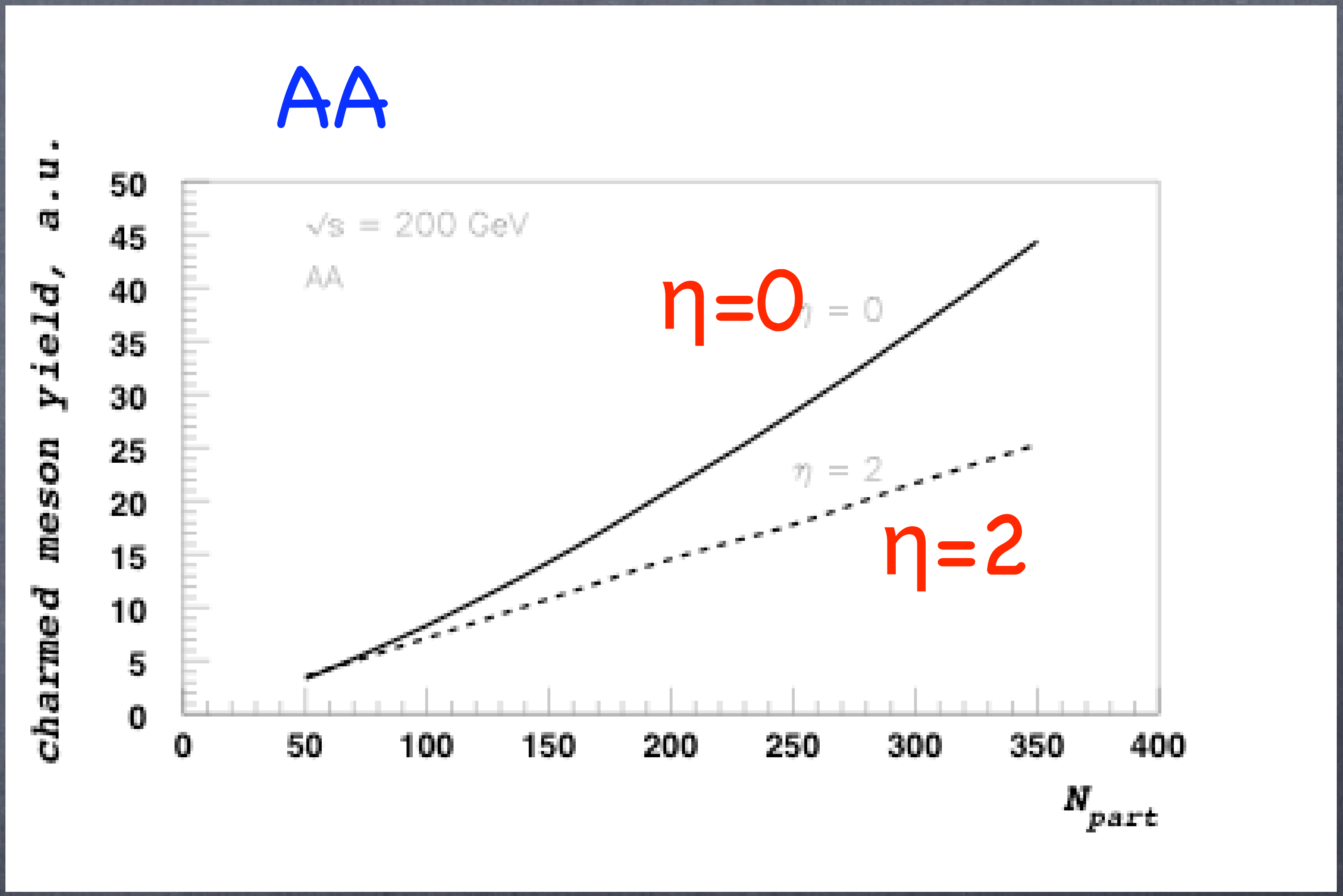


Application to RHIC phenomenology

Kharzeev, KT

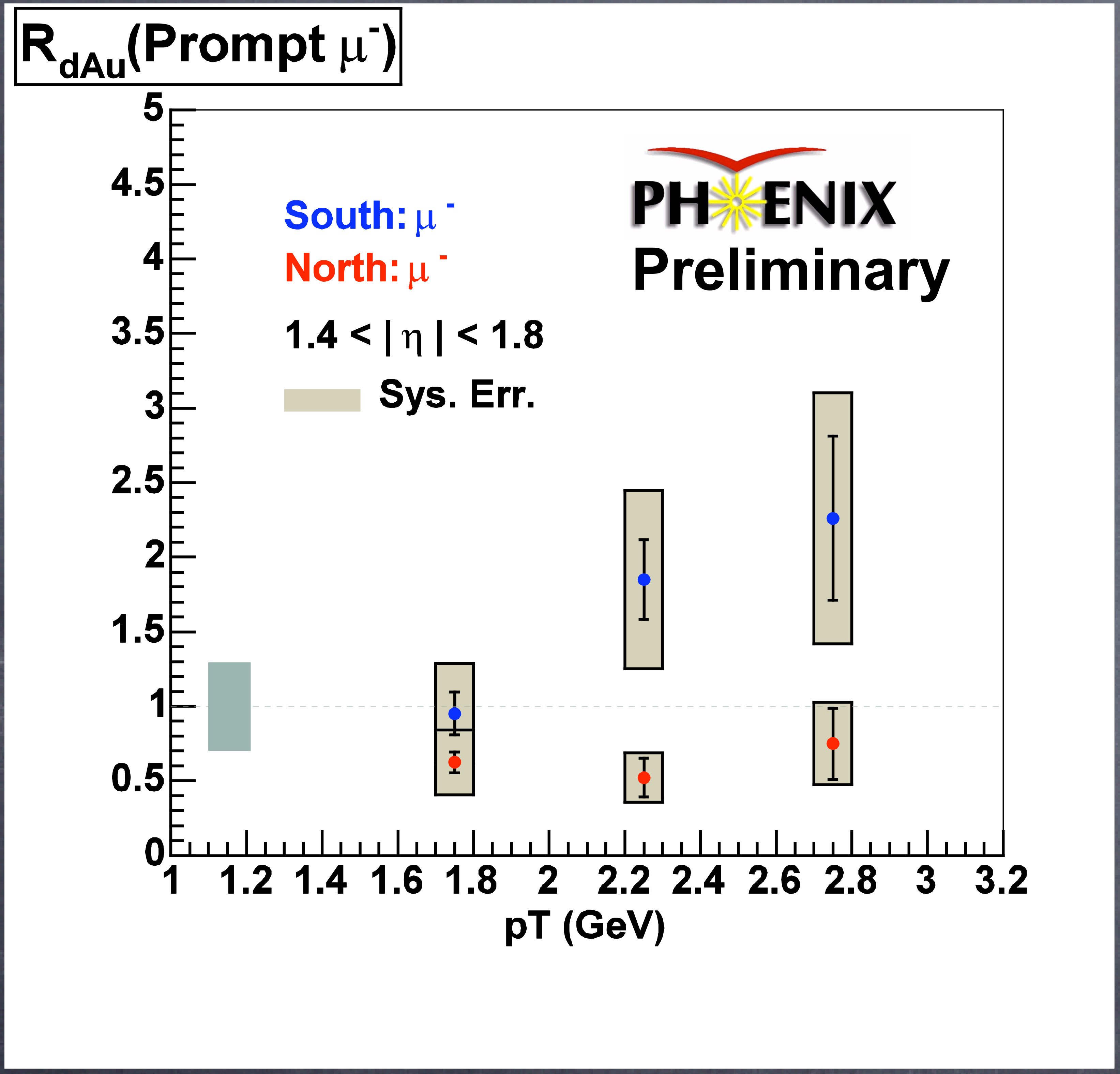
- A model based on k_T-factorization





- Suppression onsets when $Q_s > m$. Production pattern of light and heavy quarks becomes the same.

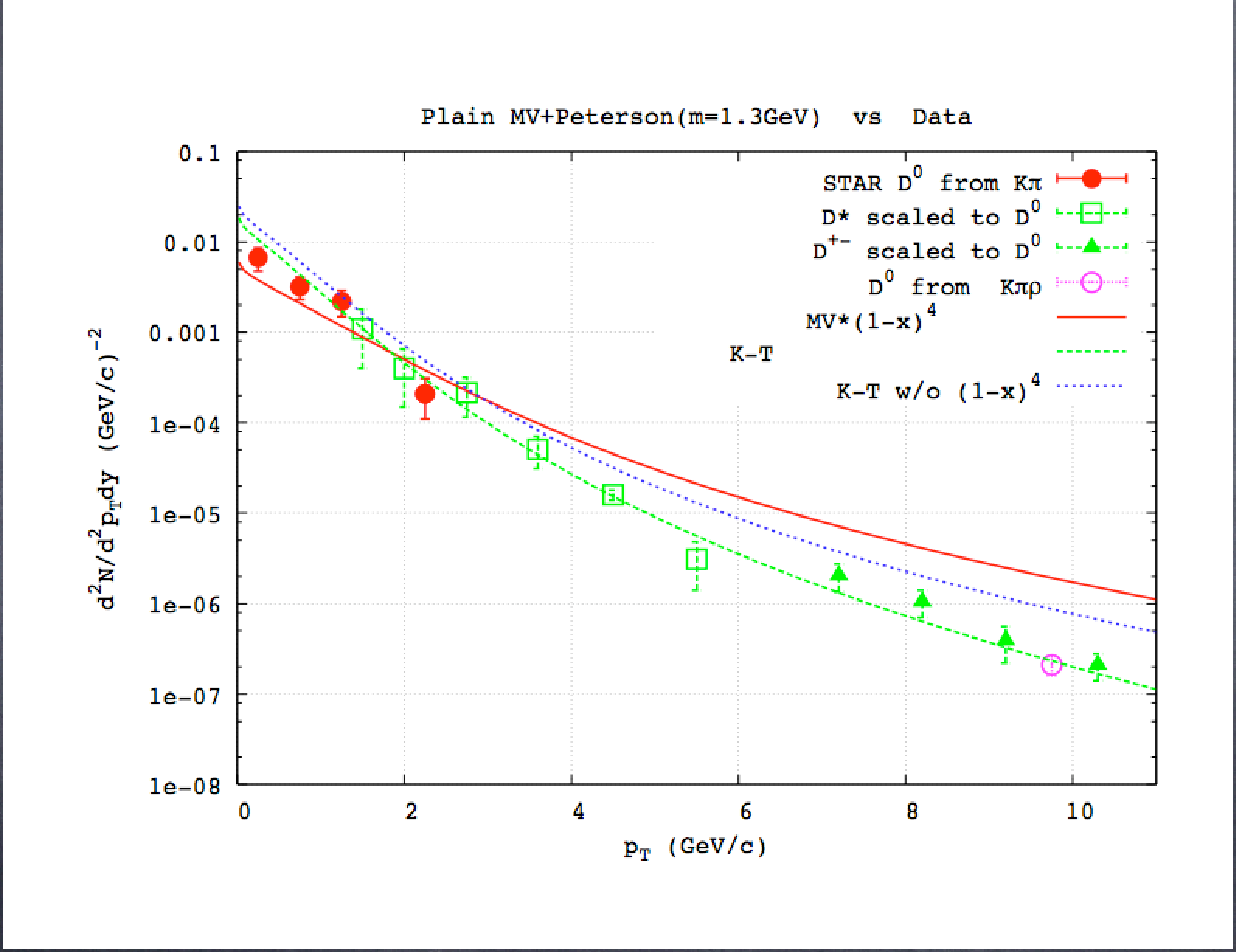
Data from PHENIX



- Both suppression at forward rapidity and enhancement at backward one are consistent with CGC.

Presented by R. Averbeck at RHIC & AGC Users' Meeting

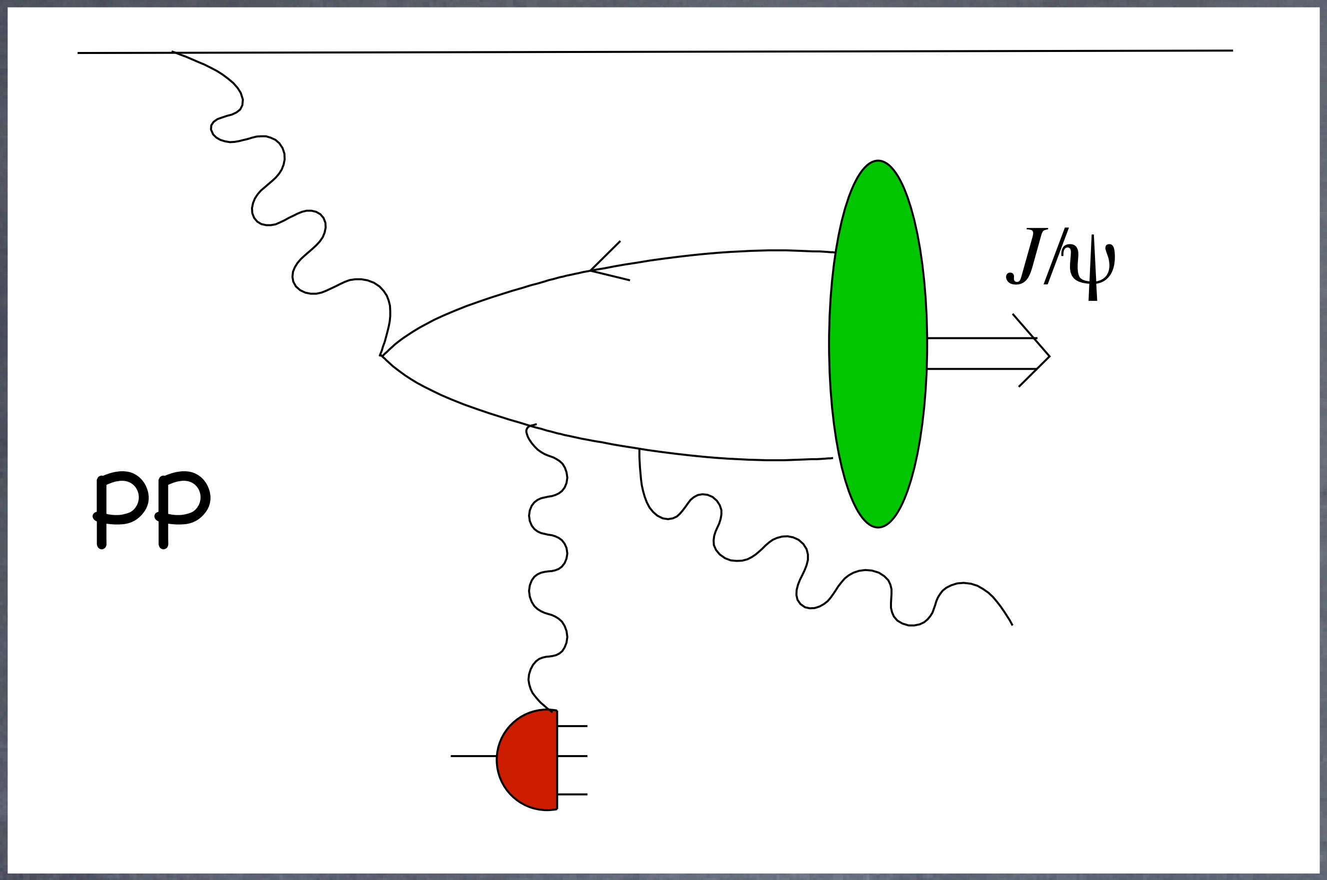
Heavy Quark Spectrum

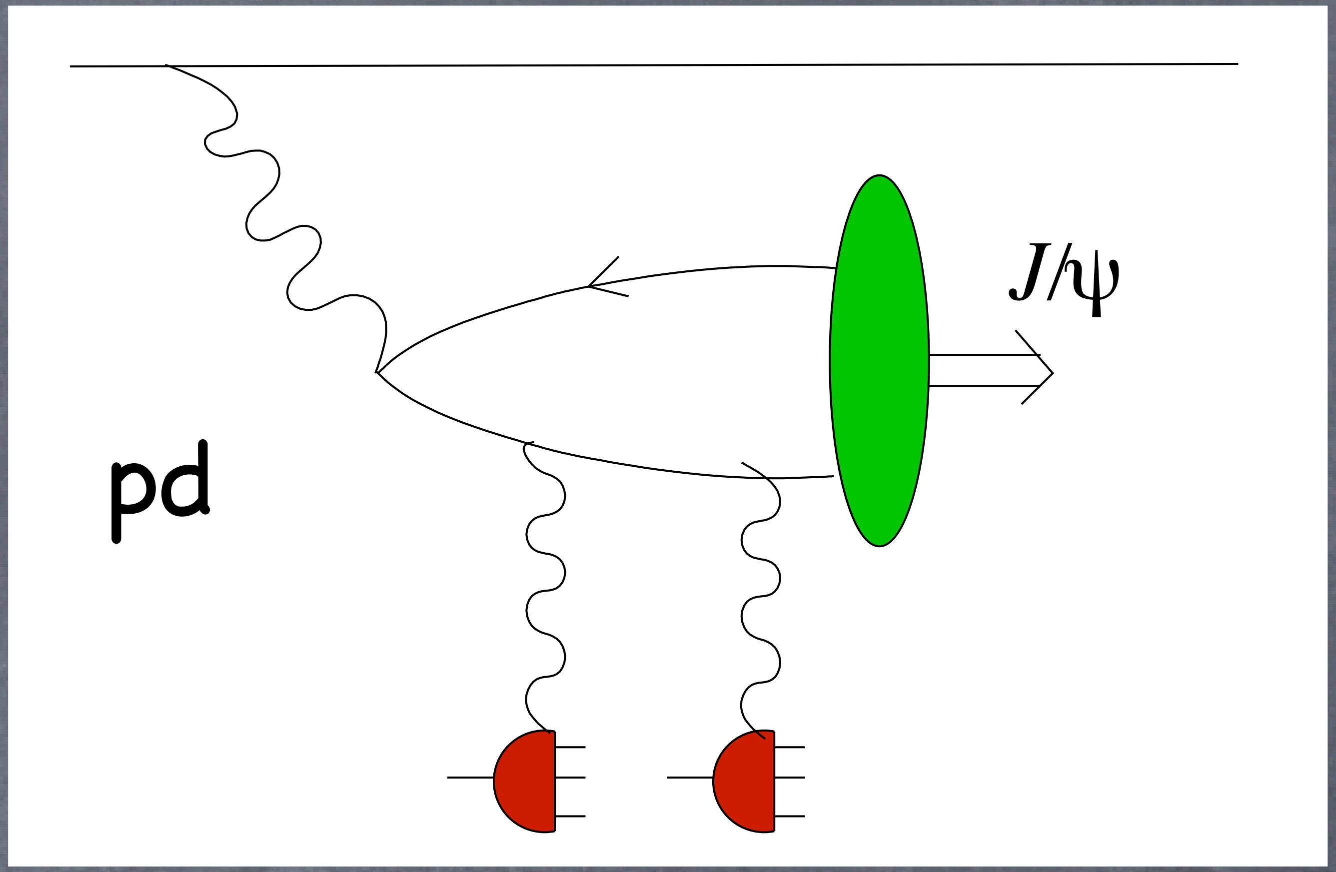


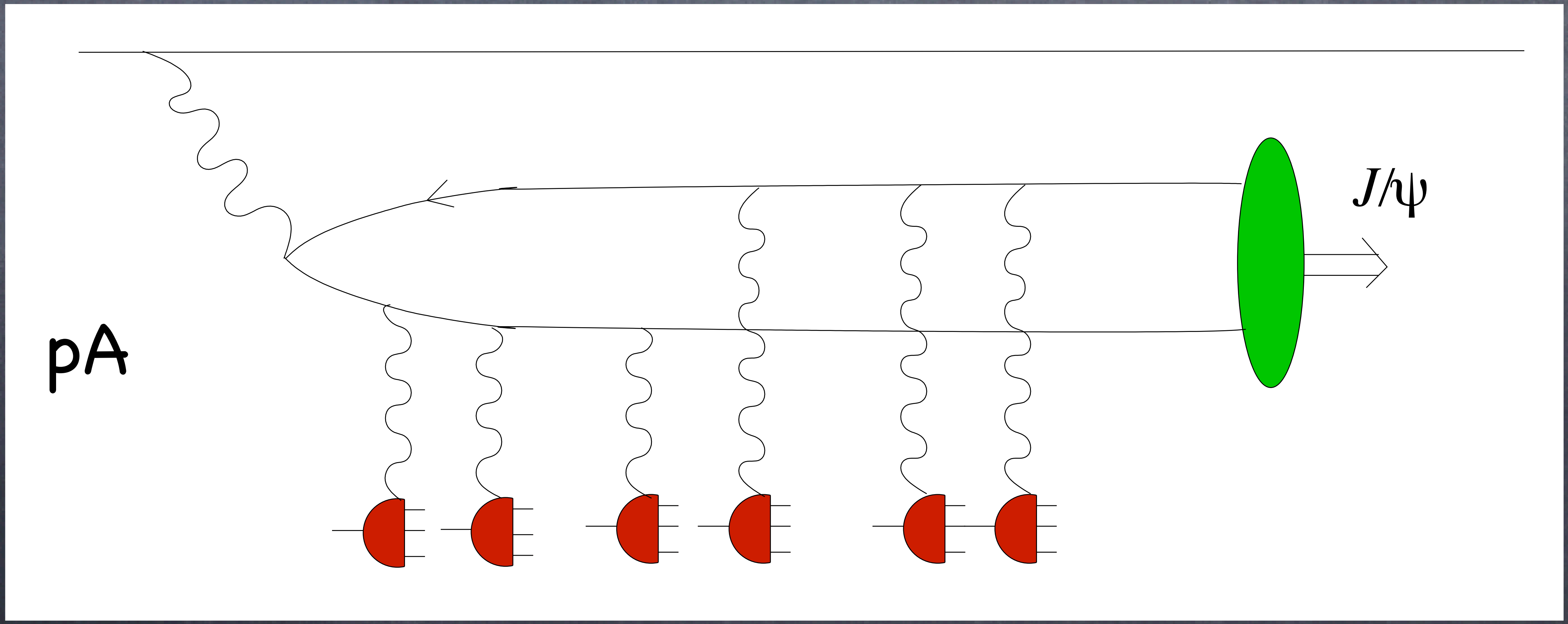
courtesy by R. Venugopalan

J/ψ production

Kharzeev and KT



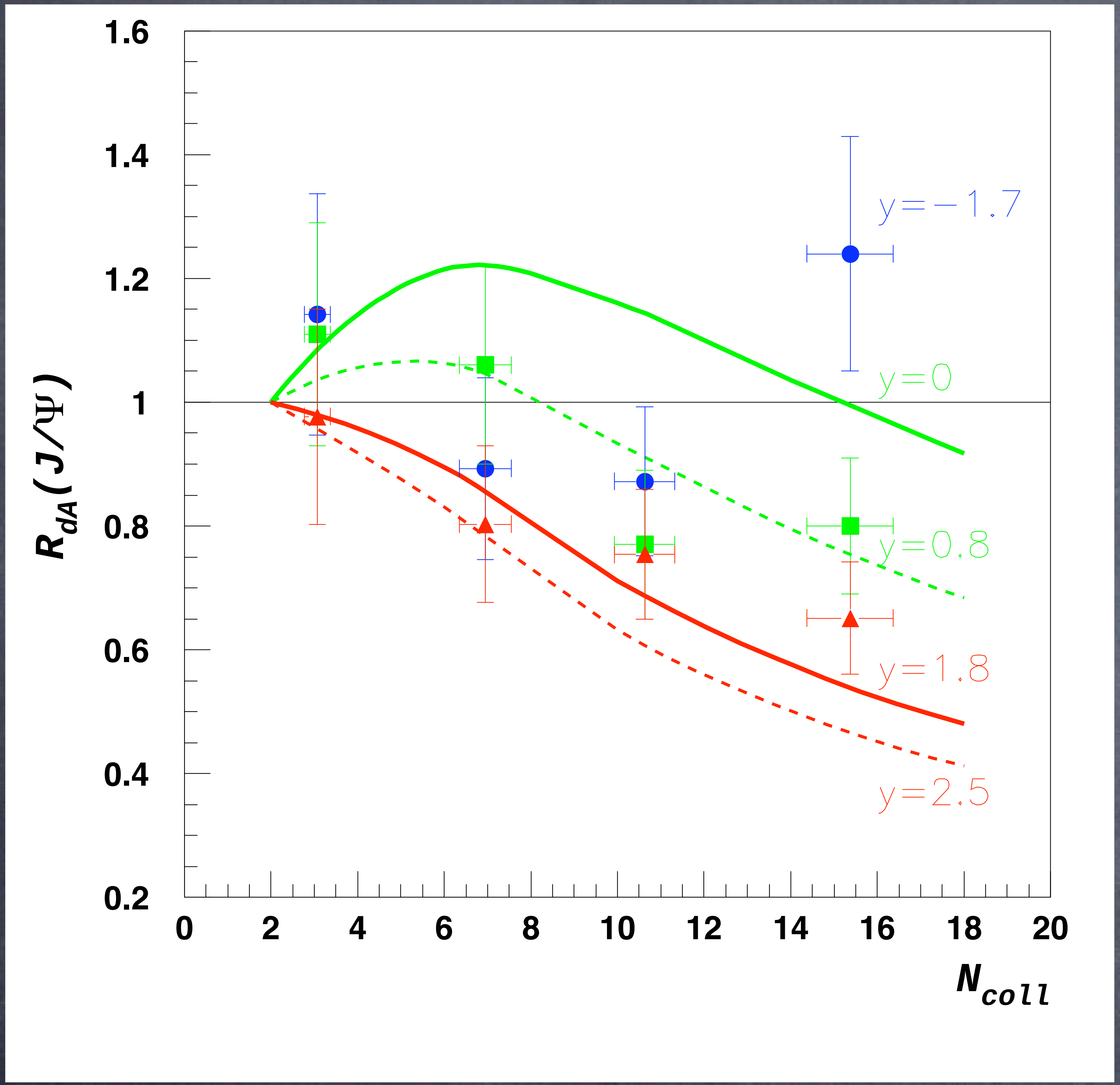


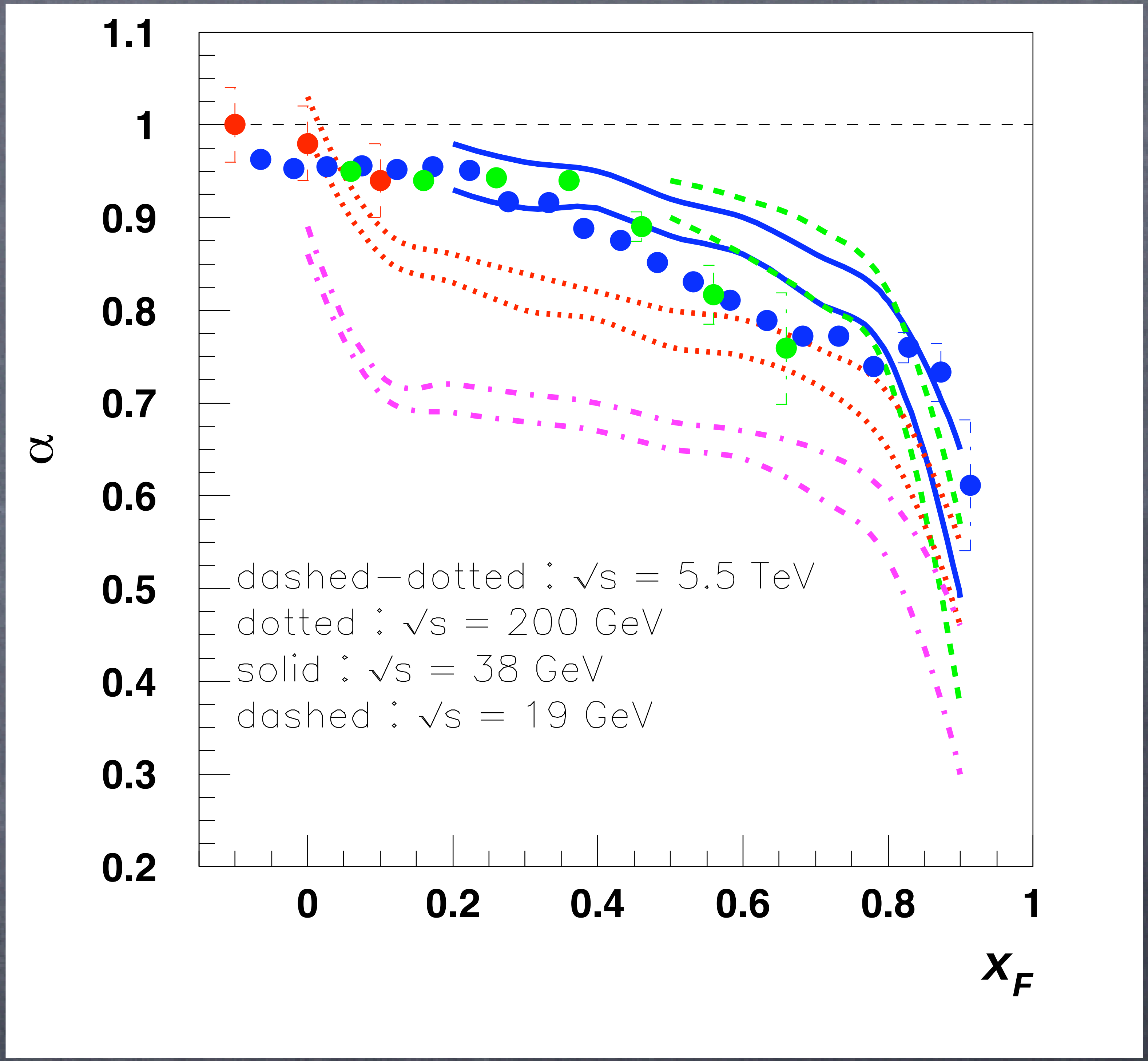


J/Ψ production

Kharzeev and KT

"x_F-scaling"



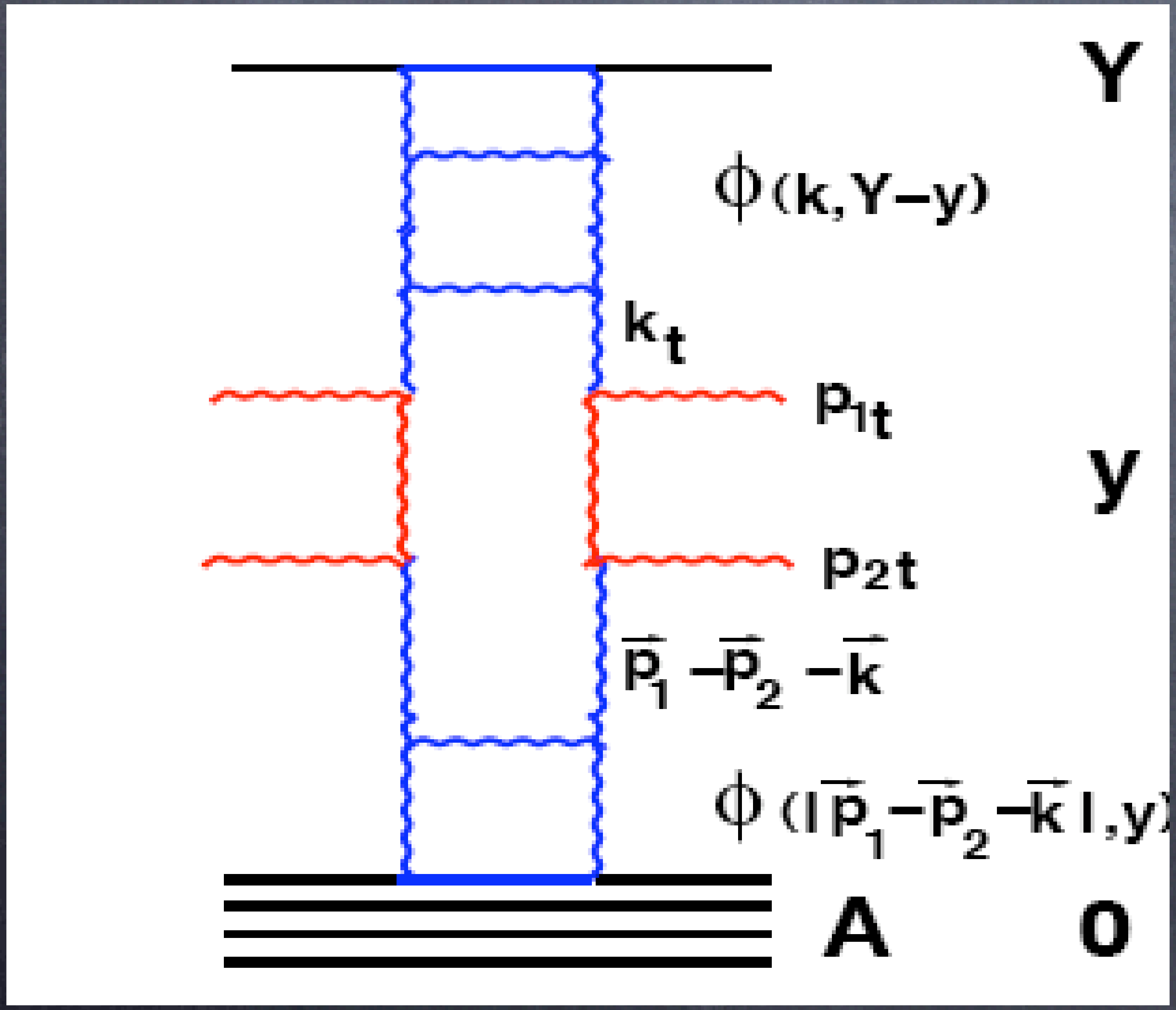


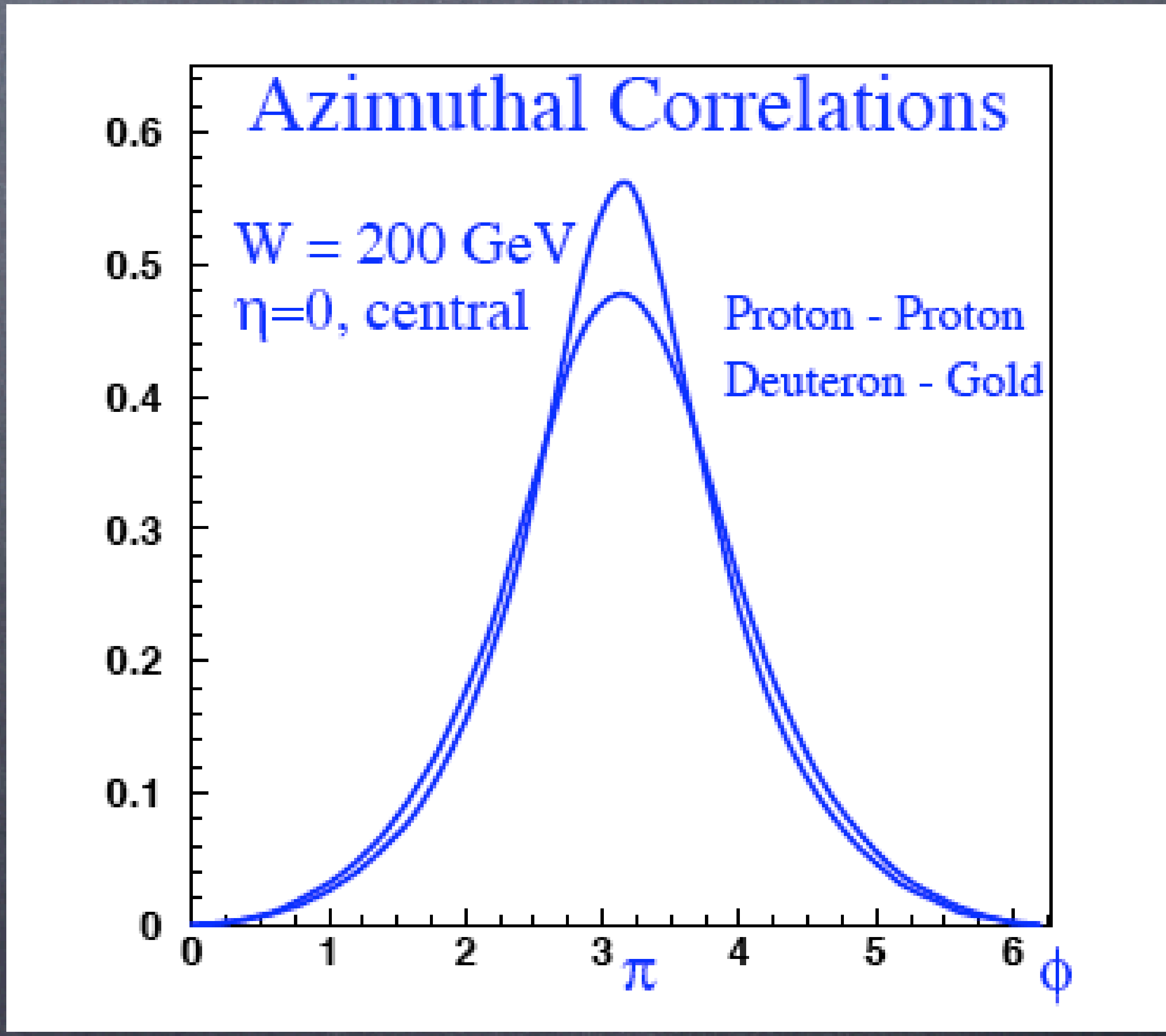
data by PHENIX

more details in the talk by Alex Kovner

Azimuthal correlations

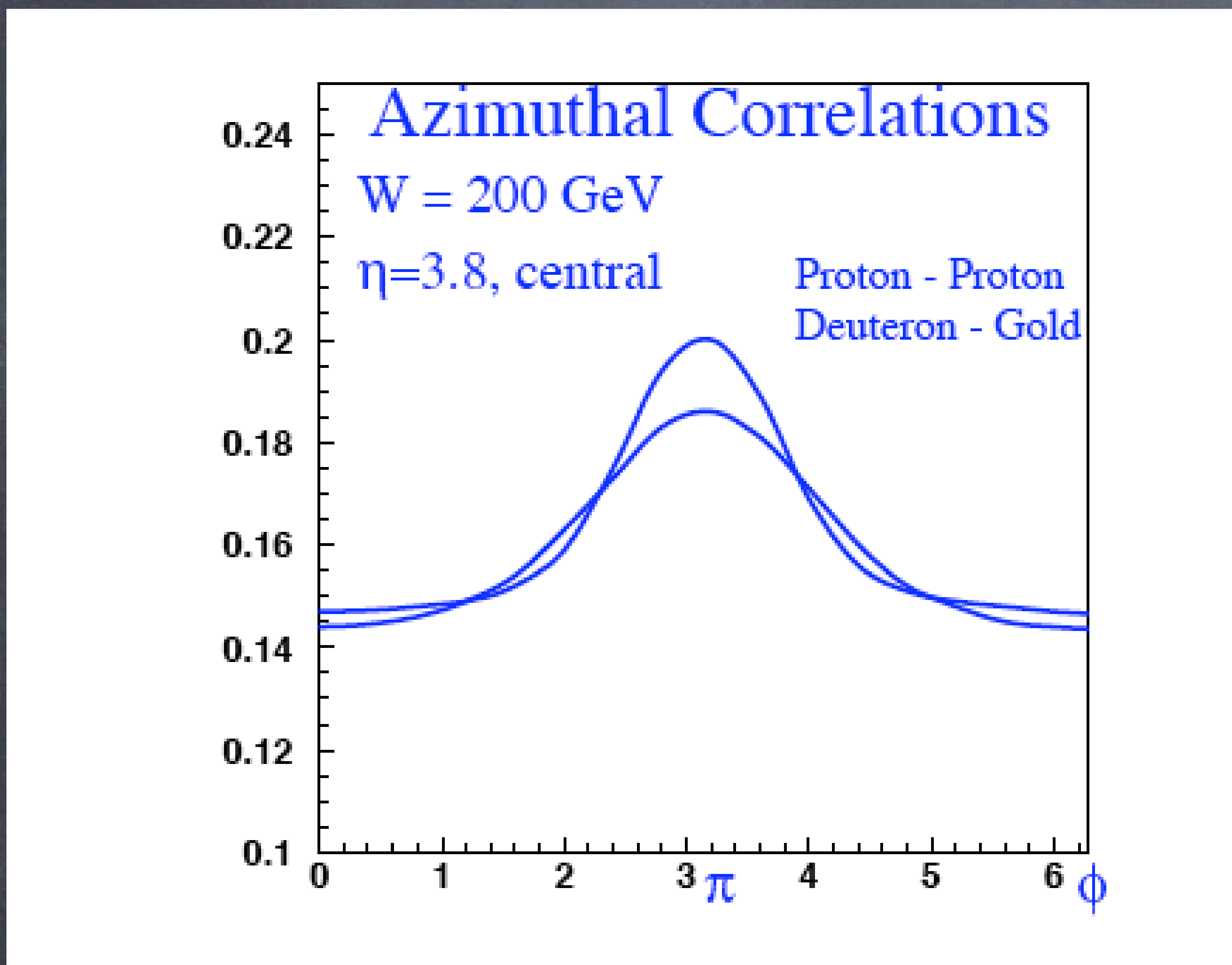
- Azimuthal correlations due to CGC are different from pQCD: they are depleted since the classical fields commute. Prediction (Kharzeev, Levin, McLerran): suppression of back-to-back correlation at low x.



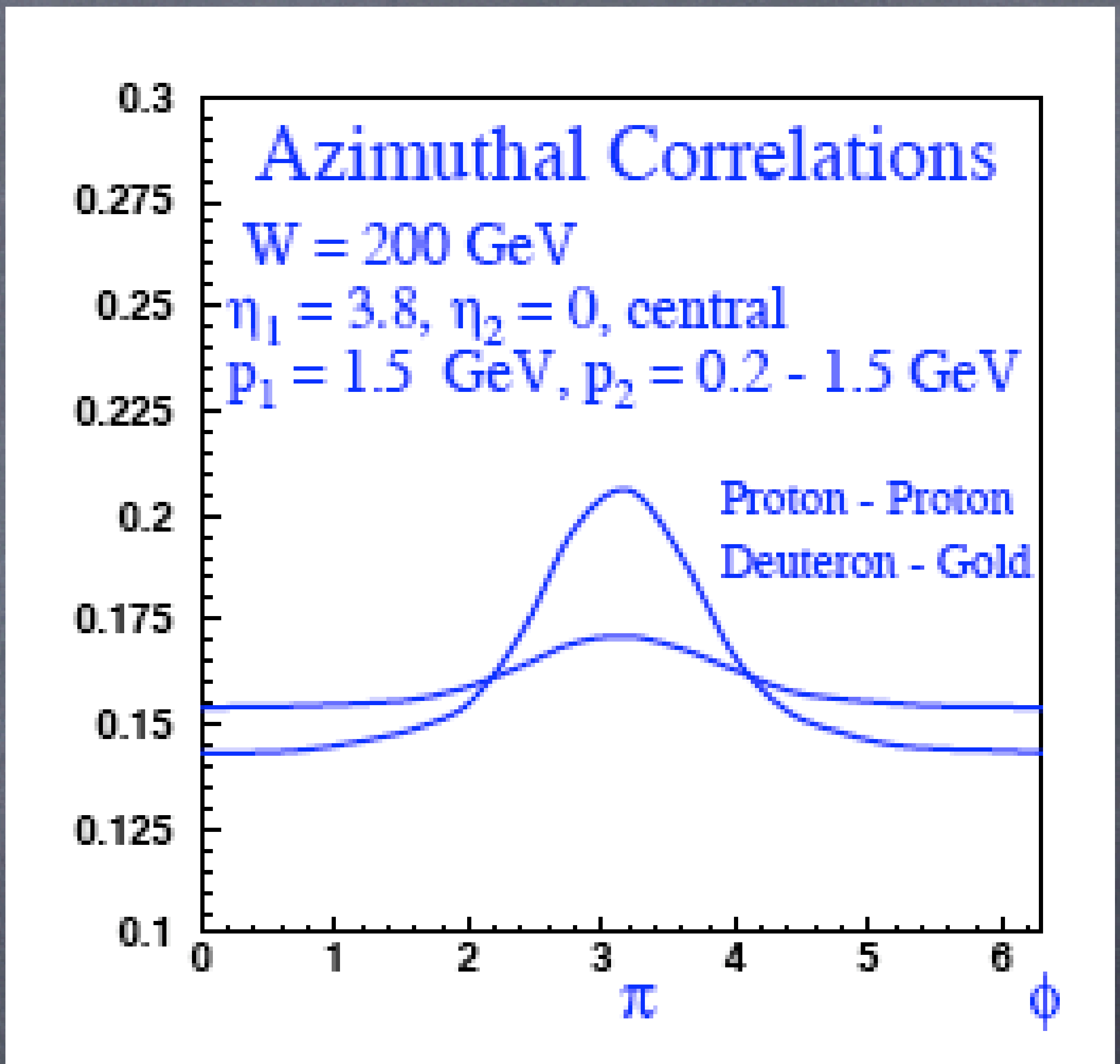


Azimuthal correlations

- at forward rapidity:



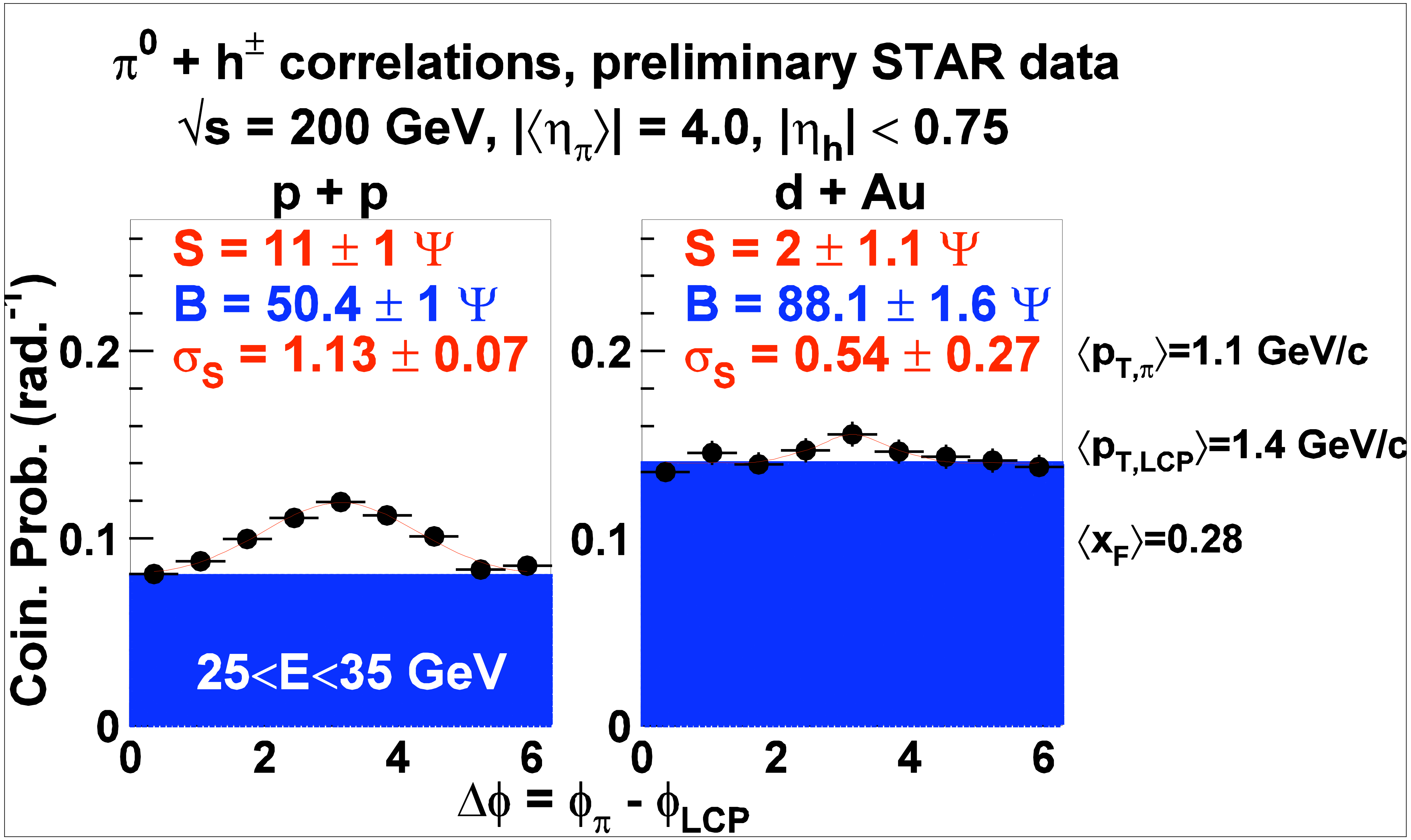
- backward-forward correlations:



- Exact calculation of the double inclusive gluon production see Jalilian-Marian, Kovchegov.

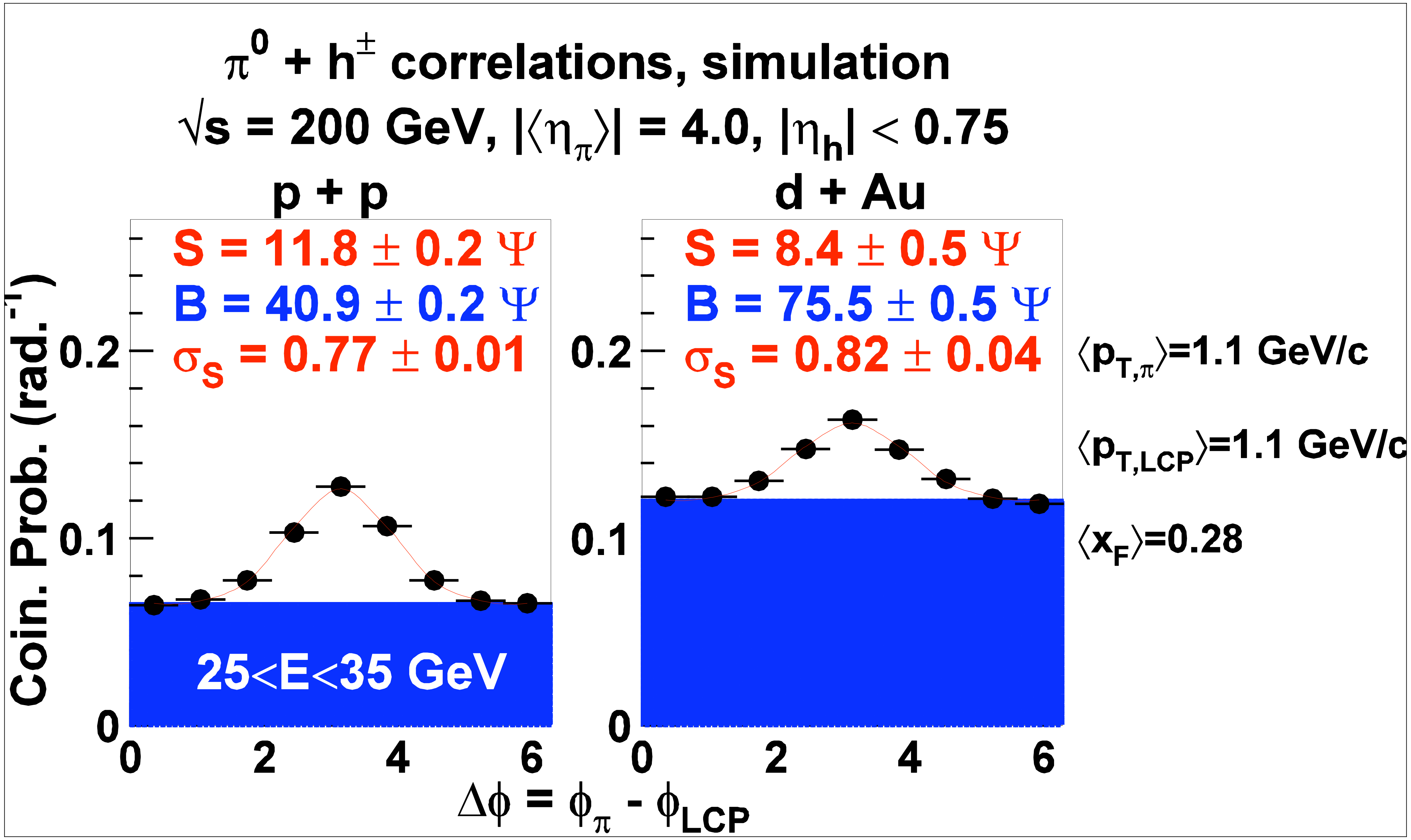
see also Baier, Kovner, Nardi, Wiedemann

Back-to-back correlations



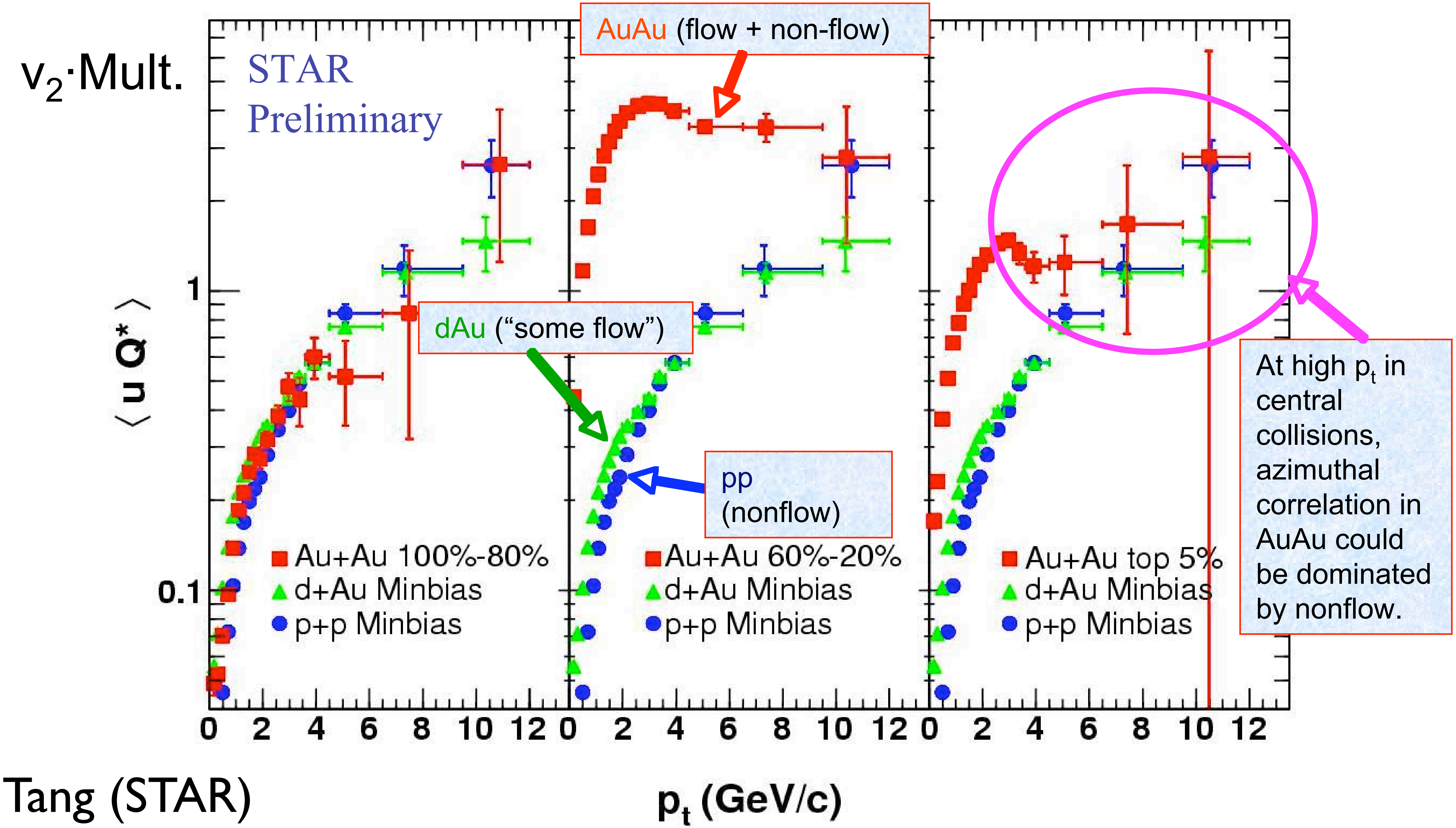
by STAR

Back-to-back correlations



from HIJING

Azimuthal correlations in AuAu, dAu and pp



by Tang (STAR)

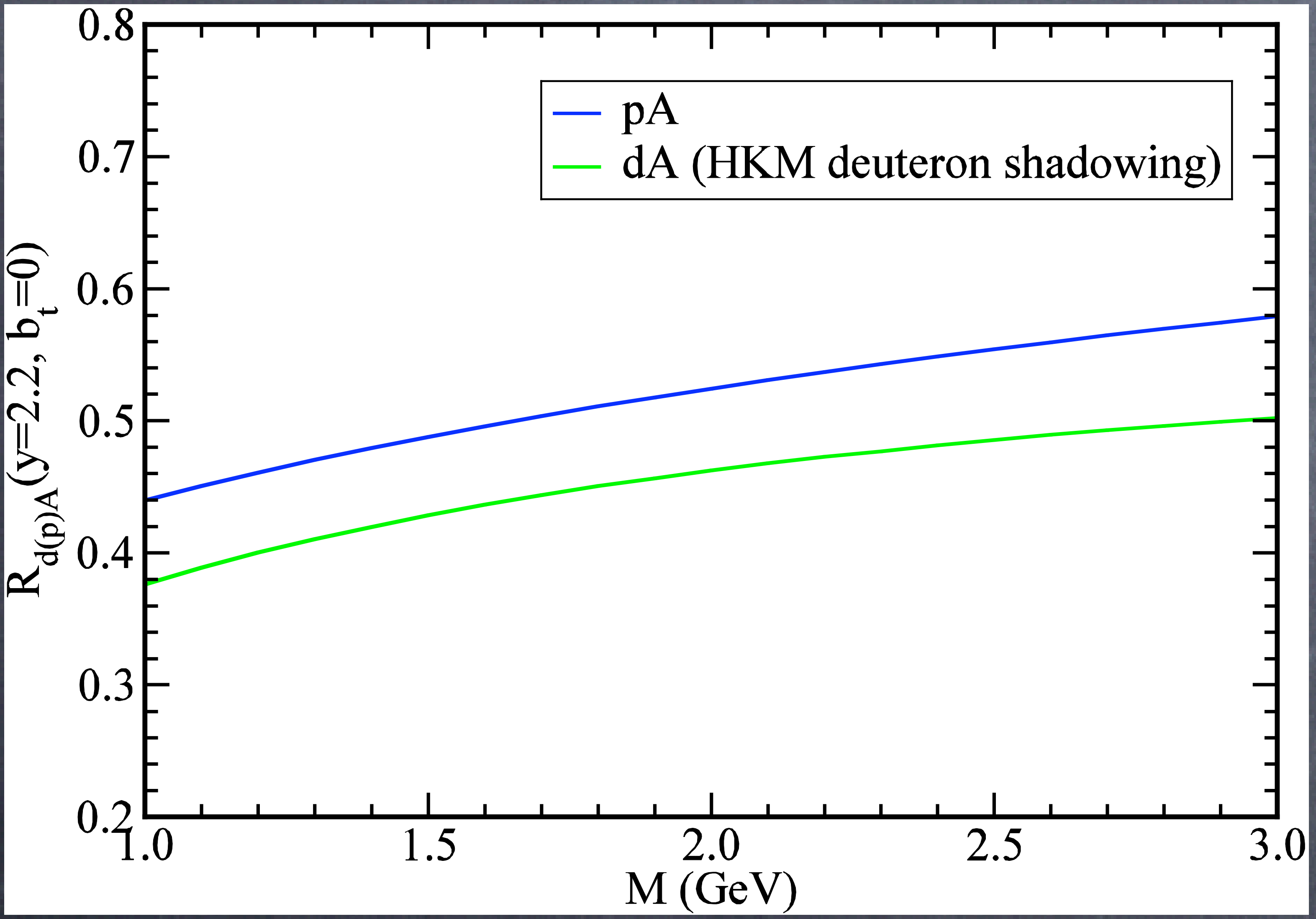
There is a significant “flow” component in dA and pp at large p_T

(Kovchegov, KT)

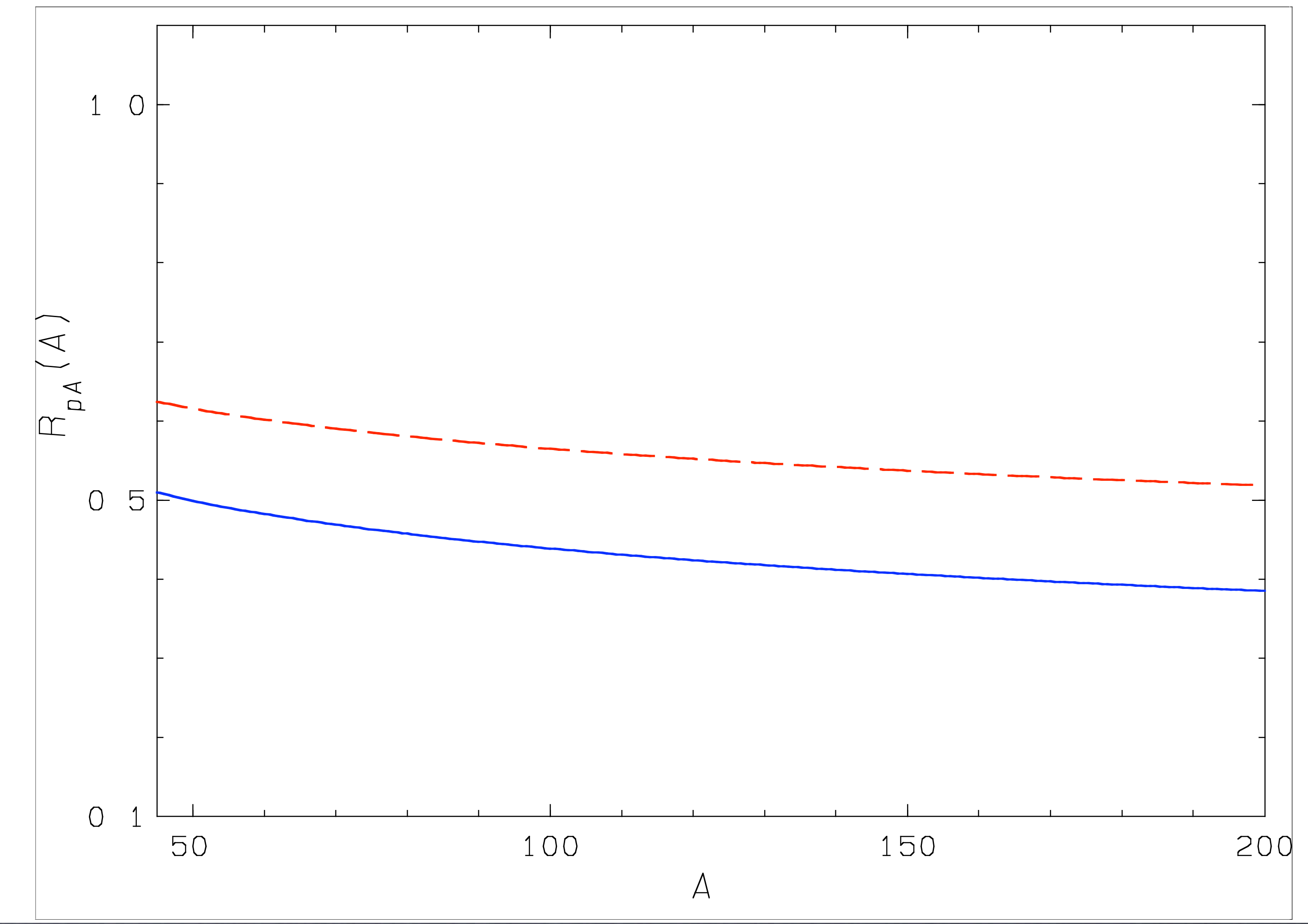
Di-lepton production

Kopeliovich, Schafer, Tarasov, (photons*); Jalilian-Marian; Baier, Mueller, Schiff

- Advantages of di-leptons:
  - ✓ no need to know the fragmentation functions;
  - ✓ do not strongly interact.



$R_{dA}(M)$ integrated over transverse momenta of lepton pair (Jalilian-Marian)



$R_{dA}(A)$ at k_T=5 GeV, M=2 and y=3 (Baier, Mueller, Schiff)

Summary: signatures of CGC in p(d)A

- Hadron spectra and multiplicities ✔
- Heavy quark spectra and multiplicities ✔ (preliminary)
- J/ψ ±
- Correlations ±
- Di-leptons ?
- Energy dependence - LHC.